



BEEYONDERS

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D3.1: Digital Twin Design and Architecture WP3, T3.1

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Acronym list

AI	Artificial Intelligence
AP	Access Point
AWL	Autonomous Wheel Loader
BPMN	Business Process Modeling and Notation
BT	Breakthrough Technologies
CP	Cloud Points
DT	Digital Twin
IoT	Internet of Things
LCCA	Life Cycle Costing Analysis
Lidar	Light Detection And Ranging
ML	Machine Learning
MQTT	Message Queuing Telemetry Transport



[D3.1: Digital Twin Design and Architecture]

PCD	Point Cloud Data
R&D	Research and development
REST	Representational State Transfer
RL	Reinforcement Learning
SDM	Smart Data Models
UAV	Unmanned aerial vehicle
UML	Unified Modeling Language
Wi-Fi	Wireless Fidelity
P2P	Pear to Pear
ABM	Agent Based Modelling
QC	Quality Control



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Executive Summary

BEEYONDERS is a R&D project funded by the European Union's Horizon Europe research and innovation program to fulfil the requirements of the topic: HORIZON-CL4-2021-TWIN-TRANSITION 01-12: Breakthrough technologies supporting technological sovereignty in construction (RIA). Its objective is to face the main challenges in construction that have been defined as: 1.-Labour shortage and lack of digital skills in some countries, 2.-Lack of motivation or young people to work in this sector and gender equality, 3.-Improvement in the safety and well-being of any age and gender workers, 4.- Resource efficiency and reduction of embodied and wasted CO₂ based on a circular economy, and 5.- Increasing the productivity while improving quality, cost efficiency and project delivery.

Deliverable 3.1 entitled "Digital Twin Design and Architecture" corresponds to the completion of Task 3.1, with the same name as this deliverable, of WP3 "Digital Twin and Diagnostics", and the sections covered in this document are as described below.

In Section 1 (Introduction), the context of the Deliverable is described, as well as its relationship to other previous, parallel, and future Project activities.

Section 2 (Users and expectations of the platform) details the user requirements in the framework of a Digital Twin in the construction sector and defines, in general terms, what is expected from the platform.

Section 3 (Use Cases and Workflows) details the operational scheme and a BPMB diagram for each use case. These workflows will converge in a general, one-fit-all workflow, that is, they will have a common part that will define the core of the data platform architecture. Likewise, the type of KPI produced as output in each use case will be listed, since this is one of the key outputs of the Digital Twin, as well as functioning as a visual repository of the data generated by the different breakthrough technologies applied in the various use cases.

Section 4 (Technical Requirements) includes tables indicating the functional requirements (the main technical characteristics of the system to meet the requirements or tasks expected by the end users) and the non-functional requirements (the requirements that do not correspond to the final functionalities of the system but solve intermediate technical needs to achieve such functionalities).

Section 5 (Modular Architecture Definition) details the different levels (Data, Acquisition and Business Layers) of the system at the IT level, as well as the communication between them. For this purpose, graphical diagrams showing the conceptual design of the Digital Twin and the data platform will be presented.

Section 6 (Platform Software Environment) describes and justifies the selected technology options, in as much detail as possible at the date of this document (prior to IT implementation and use case testing). In addition, the steps to be followed in such development leading to an operational validation are discussed.

Section 7 (Visualization Interfaces) defines the visualization tools: proprietary, existing free tools to be incorporated in the process, and other standard tools in certain sub-processes that might be considered necessary.

Finally, Section 8 (Conclusions) summarizes the key aspects of the proposed design of the Digital Twin and the Data Platform, as well as what is expected in relation to the next tasks, including the development and practical implementation of the design.



Introduction

Context

In recent years, the use of Digital Twin technology has gained popularity in various industries, including construction. A construction digital twin is a virtual replica of a physical building or infrastructure that simulates its behavior and performance in real-time (or near-real time, depending on the application). It allows architects, engineers, contractors, and project managers to visualize, analyze, and optimize the design, construction, and operation of a building or infrastructure project. BEEYONDERS transcends this concept, still in its infancy in the construction sector, by integrating operational information from different cutting-edge technologies, namely autonomous construction machines, drones, additive manufacturing, and exoskeleton plus smart wearables (worker centric devices) for health and safety, into the DT.

A Digital Twin is proposed to be used for monitoring, diagnostics, and prognostics to optimize asset performance and utilization of the technologies proposed in the project that will be deployed in the case studies. Complex prognostics modules based in Digital Twin will find the root cause of issues and improve productivity, planning performance, health & safety of workers and environmental impact.

In this context, this deliverable D3.1 collects the fundamental aspects of BEEYONDERS digital twin architecture design, that will be deployed for the different project use cases. It will examine the different components of the architecture, the challenges involved, and the best practices to ensure successful implementation.

The architecture design encompasses the hardware, software, data, and networking components required to build, operate, and maintain the digital twin. The architecture design should consider factors such as scalability, interoperability, security, and data privacy.

The architecture here proposed has been designed according to first understanding how the use cases are going to be performed, and their requirements combining the information provided in D2.2 – Technical Requirements, and workshops that have been organized during this task to extend the details of the use cases. Workflows for each use case are presented here to identify data exchange required with DT in/out during the perform of use cases, and to identify the steps where DT is crucial.

Architecture proposed here pretends to follow a modular and flexible approach, able to integrate different data sources of BEEYONDERS technologies, and be adaptable to future changes.

Relation with other activities

Related to this activity are:

- Each BEEYONDERS technology that will send / receive data to DT. Namely:
 - Autonomous wheel loader (AWL hereafter)
 - Unmanned Aerial Vehicle (UAV hereafter), with indoor and outdoor drone models
 - Giken Ltd push-in pile system
 - Autonomous inspection mobile platform
 - Additive manufacturing (3D printable caisson)



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- Exoskeleton
 - Smart Wearables (SMW hereafter)
 - Agent Based Modelling software (ABM)
- D2.2 – Deliverable "Technical Requirements", already submitted in November 2022.
 - All WP3 of "Digital Twin and Diagnostics". In particular, this deliverable, which corresponds to the end of task T3.1 "Digital Twin Design and Architecture", marks the starting point for the subsequent ones:
 - T3.2 – Digital Twin Platform & Interaction Interfaces.
 - T3.3 – Data Sources Integration.
 - T3.4 – BIM Updating Service.
 - T3.5 – Digital Twin Services Input.
 - T3.6 – Digital Twin Services Output.
 - T3.7 – Training & Learning Environment.
 - KPIs to be defined in D2.3 – LCA/LCC KPIs and D2.4 – Workers KPIs.
 - D2.5 – Testing Plan and Report, where the testing Plan is going to evaluate the DT operations.
 - Use cases of WP7.

Means of verification: D.2.5, D3.2, D3.3, D3.4, D3.5, D3.6, D3.7, D7.2, D7.3, D7.4, D7.5 and D7.6

KPIs: Progress in TRL / Interoperability of data and systems / Productivity indicators of DT outputs

Below (see Figure 1) is a conceptual scheme that shows how the different Technologies are collected in the use cases through the DT, with details of the conceptual design that starts at the beginning of WP3 (led by TEC), and corresponds to the present task, and the part that is addressed at the beginning of WP4 (led by ITA).

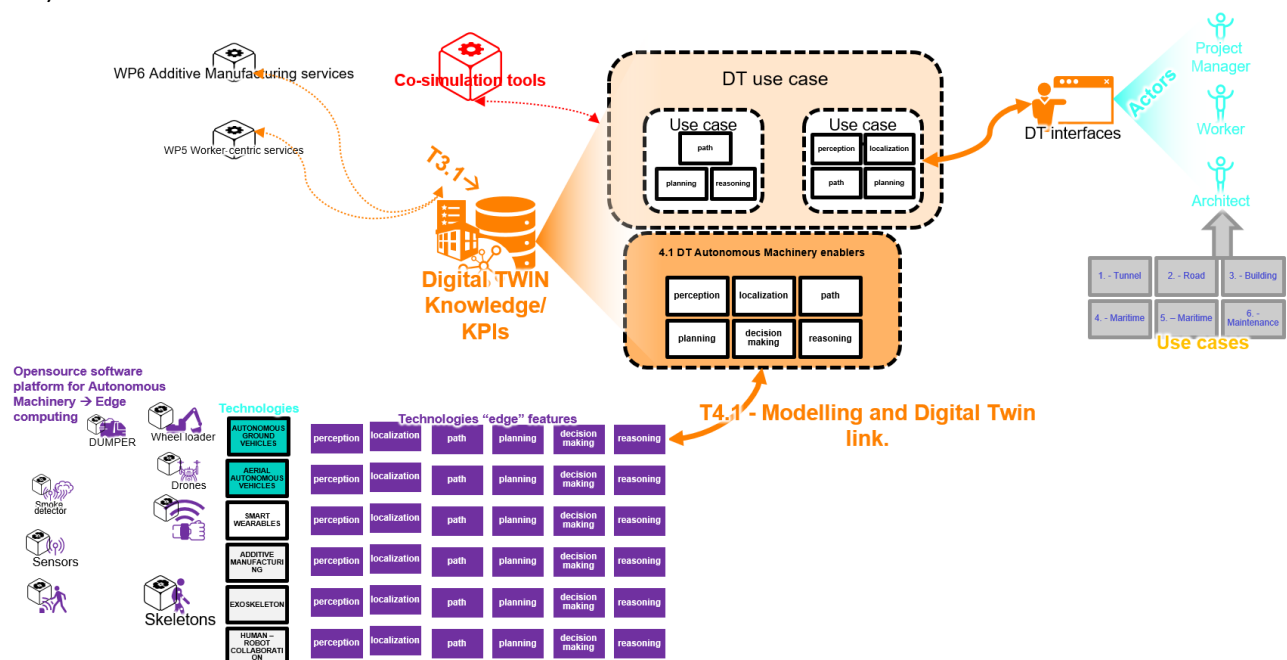


Figure 1. T4.1 Digital Twin and Autonomous vehicles Link



Users and expectations of the platform

User roles

In the construction domain, a digital model is still restricted to the stage of a static designed BIM model. The more developed application area remains limited to building design and planning work tasks instead of taking advantage of the rich data that is available in construction operations, as the workers performance and safety, environmental aspects, or automated devices. In BEEYONDERS, the aim is to:

- Implement and integrate into a common environment platform the BEEYONDERS BTs in construction work process, in which decision are supported by the BTs key information.
- Provide the full situational awareness as expressed in alternative planning through performed construction site status modelling (in terms of productivity), workers KPIs and environmental impacts.

Thus, a Digital Twin (DT) platform will bring together data acquisition during the case studies to manage the information of BT developed and demonstrated, with a set of layers and applications based on AI for decision-making and improvement of wellbeing & safety of workers. This will be done in such a way as to meet the following Project objectives:

- DT design, architecture, interfaces, common data formats and communication protocols defined, developed, tested, and demonstrated.
- AI-capabilities integrated with DT developed, tested, and demonstrated to assess the H&S of workers in collaborative environment with the BT.
- AI-capabilities integrated with DT developed, tested, and demonstrated to assess the productivity & planning of the construction site with the BT.
- Integrate LCA&LCC KPIs for analysing all project developments based on BT design and defined.

According to the above, the key element to be generated is a BEEYONDERS Digital Twin platform, which will have to meet several performance expectations, which leverages capabilities of BEEYONDERS machines/devices. An immediate picture (see Figure 2) of this approach is shown in the schematic below (DT to be developed in this WP3, while the link between DT and BT, and their cooperation outside the work package, will be developed mostly in WP4 but also with contributions in WP5 and WP6).



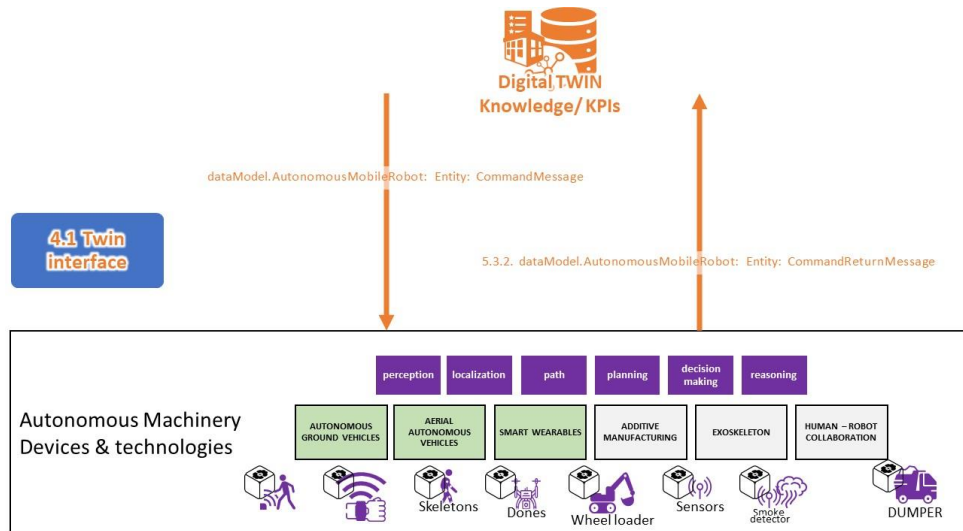


Figure 2. T4.1 Digital Twin and BT

In a construction digital twin, various user roles are involved in creating, maintaining, and utilizing the virtual replica of the physical building or infrastructure. The following are some of the user roles in a construction digital twin:

- **Architects and Engineers:** Architects and engineers are responsible for designing the building or infrastructure project and providing specifications and requirements for the digital twin. They work with the digital twin team to ensure that the virtual replica matches the physical design.
- **Contractors:** Contractors use the digital twin to plan and execute construction activities. They can visualize the building or infrastructure project in the digital twin to identify potential problems and optimize the construction process.
- **Project Managers:** Project managers utilize the digital twin to track the progress of the construction project and ensure that it is on schedule and within budget. They can monitor various aspects of the project in real-time using the digital twin.
- **Facility Managers:** Facility managers use the digital twin to manage the building or infrastructure after construction is complete. They can monitor the performance of systems such as HVAC, lighting, and security to optimize energy usage and improve the occupant experience.
- **Building Owners:** Building owners can use the digital twin to monitor the building's performance and ensure that it meets their requirements. They can use the virtual replica to identify maintenance issues and optimize the building's operations.
- **Occupants:** Occupants can benefit from the digital twin by accessing real-time information about the building or infrastructure, such as room temperature, lighting, and air quality. This information can help them improve their productivity, comfort, and well-being.

Overall, the construction digital twin provides a platform for collaboration among different stakeholders involved in the construction, operation, and maintenance of a building or infrastructure project. By leveraging the expertise of different user roles, the digital twin can help to create more efficient, sustainable, and resilient buildings and infrastructure. In BEEYONDERS, it has been identified different user roles for each Use Cases that are presented below (see Table 1):



Tunnel construction actors	Road construction actors	Building construction actors	Maritime construction actors	Maritime construction Japan actors	Road maintenance actors
Design team	Design team	Design team	Design team	Design team	Drone pilot
Drone pilot	Drone pilot	Drone pilot	DT manager	DT manager	DT manager
DT manager	DT manager	DT manager	Field worker	Field worker	Field worker
Field worker	Field worker	Field worker	Project leader	Project leader	Project leader
Project leader	Project leader	Project leader	Project owner	Project owner	Project owner
Project owner	Project owner	Project owner	Sensor installer	Sensor installer	Autonomous inspection platform operating team
Sensor installer	Sensor installer	Sensor installer	Marine environmental team	Geotechnical engineers	
Tunnel owner	Wheel loader pilot	Smart Wearables team	Additive manufacturing team	Pile installation machine operators	
Wheel loader pilot	Dumper pilot	Exoskeleton team	Port owners		
Dumper pilot	Smart Wearables team				

Table 1. User Roles in BEEYONDERS for each case study

Expectations from the platform

The main objective is to develop a unified, open, data platform to store, gather and analyse all numerical information describing the construction site and produced by all actors and equipment. The core component of this platform will be a digital twin of the construction site. The following image (Figure 3) shows an outline of this idea.



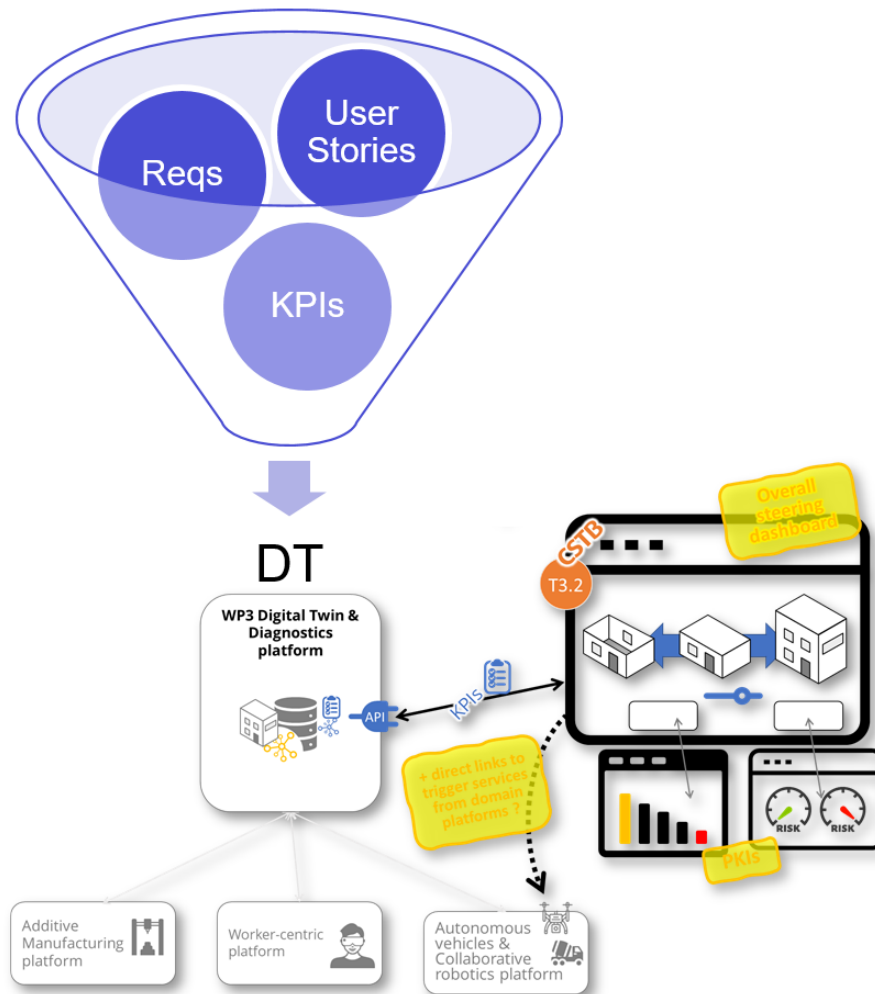


Figure 3. Expectations from the platform

By way of summary and as already mentioned, the results obtained in BEEYONDERS will be centralised and assessed in the Digital Twin environment. A fully integrated Digital Twin must be specified, implemented, and stored in dedicated databases. The initial Digital Twin model is built, through specific data importer (static data importation layer), from the BIM models provided by the conception phases of the project or point clouds captured and processed by the UAVs, and from initial planification data. This model is connected to a set of “Input services”, that will produce the specific indicators based on the KPIs defined in WP2. All the “active” parts of the construction site (workers, equipment, machines, robots, drones) will provide, through sensors, a big amount of information (positions, orientations, cloud points, distances, ...). All this information will be plugged to the Digital Twin and treated by dedicated “Output services”.

The Digital Twin will be directly linked to the technological work packages (WP4 "Autonomous vehicles and collaborative robotics", WP5 "Worker-centric technologies to improve health, safety, and well-being" and WP6 "Additive Manufacturing") as these technologies are integrated into the DT via sending their data and information collected once these are performing activities on WP7. During the case studies, DT models from these case studies are generated and employed to learning purposes in WP5, providing realistic scenarios, and related to BEEYONDERS risks & hazards related to the deployment of BT on construction sites. Diagnostics results are obtained from the WP7 performance and employed in WP8 as part of the communication & dissemination activities as a visible result of BEEYONDERS.



[D3.1: Digital Twin Design and Architecture]

Informal general explanations of software functions written from the end user's perspective are known as User Stories. Their purpose is to articulate how a software function will provide value to the end user.

The methodology used in this Deliverable (see Figure 4) consists in determining the workflows synthesized in key points for each use case with its corresponding graphic representation in the form of a BPMN diagram, extrapolated from the knowledge of user stories. User stories are the outputs of numerous meetings along WP3 to find the most accurate description possible to the use case definition.

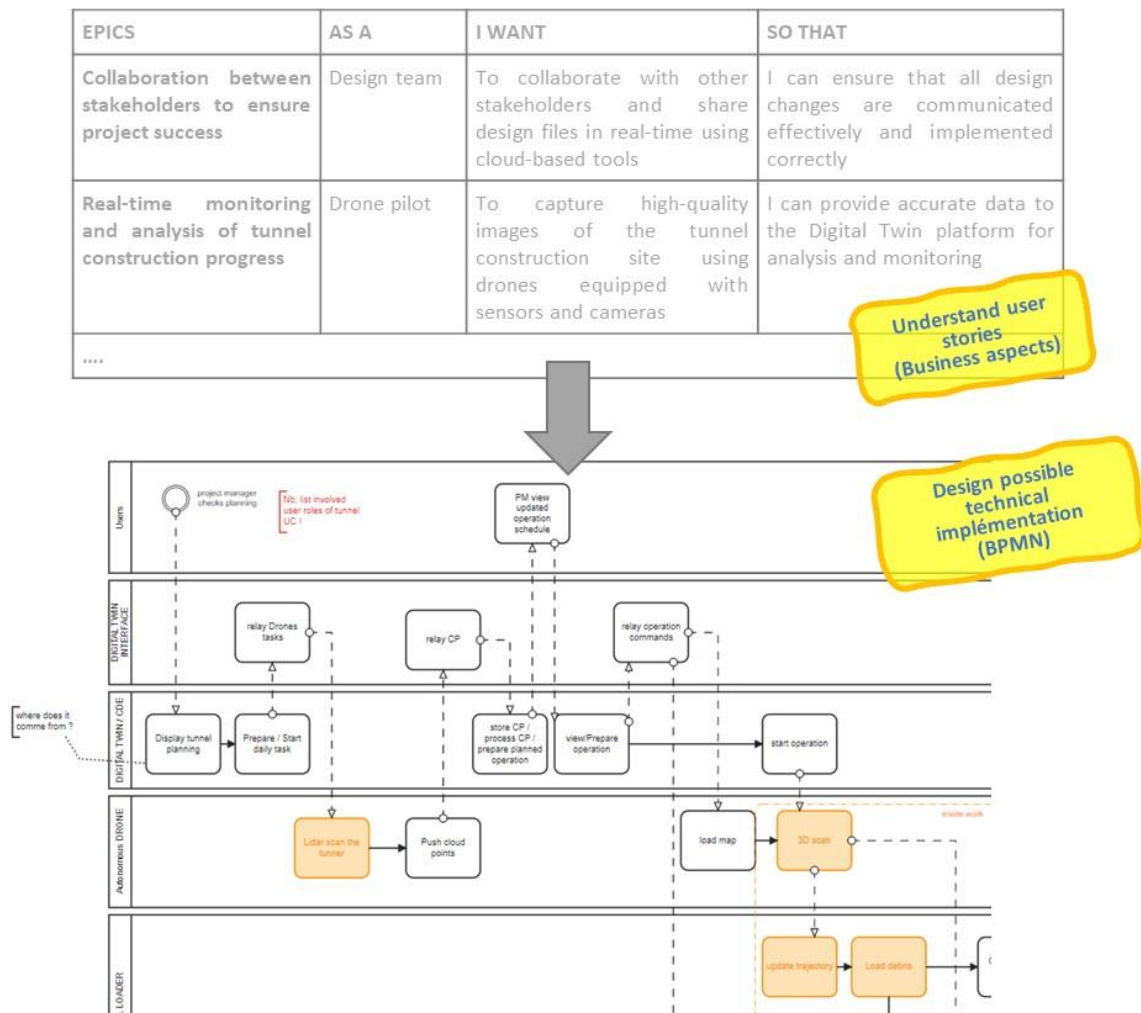


Figure 4. Requirements Elicitation Process



Workflows for the use cases

After a series of meetings between the project participants (general meetings with all the partners with special attention to the use case managers, and later meetings with including only WP3 developers), the workflows for each use case have been defined with the list of steps to be followed to complete them successfully. Furthermore, the necessary data exchange with the DT during the execution of the use cases has been identified, identifying the steps in which the DT plays a relevant role, as well as the KPIs to be produced as output. As explained in previous sections, the interrelationships between the different BTs and between the BTs and the DT will be shown in a BPMN diagram for each use case, so that the identified steps for the resolution of the works at the different construction sites are satisfied (see Figure 5).

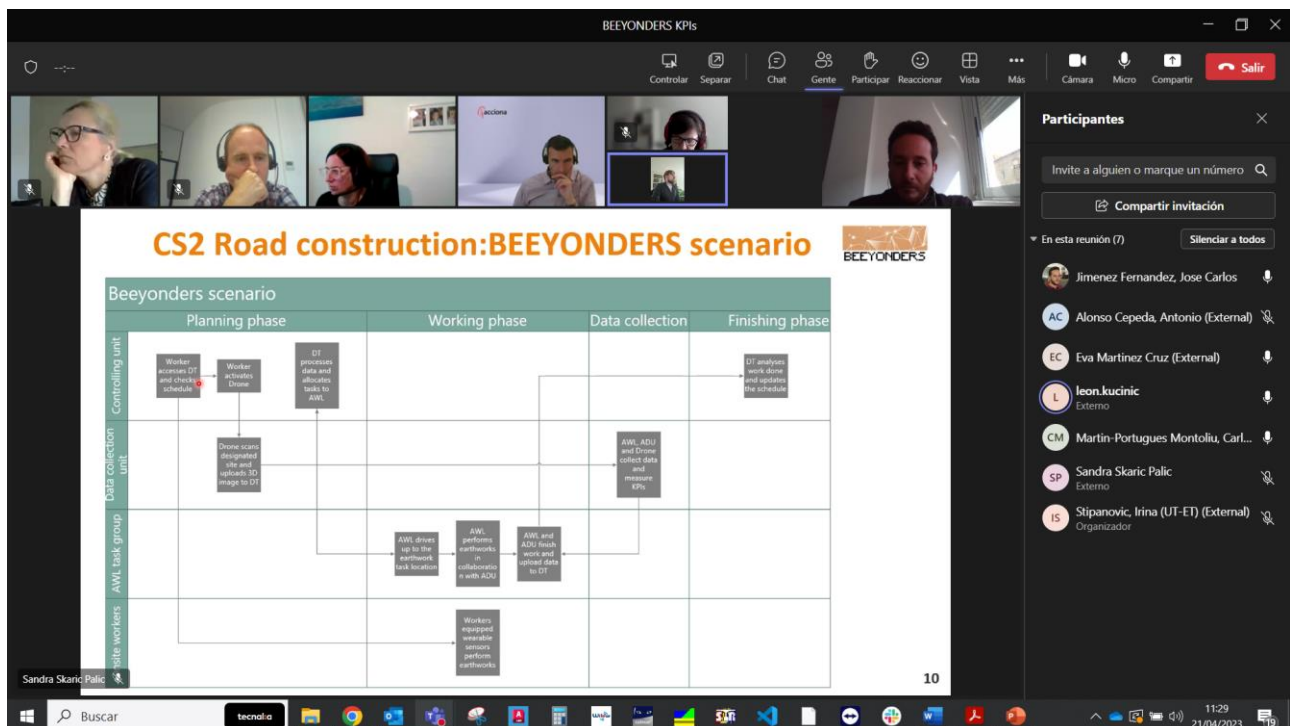


Figure 5. Use Cases Workflow Definition Sessions

Tunnel Construction

In this use case BEEYONDERS proposes a solution to the unproductive waits that occur in the construction of tunnels by the traditional method, in which blasting is performed being necessary a long wait until the workers can enter once the extraction systems purify the environment inside the tunnel. The new BTs consisting of autonomous and teleoperated robotics (AWL) guided by the information gathered by a specially designed drone (UAV), whose capabilities are intended to be demonstrated in a use case of a test tunnel located in León (Spain), will allow to perform debris removal tasks and evacuation of material to the outside before the atmosphere becomes unbreathable. A record of the progress of the vehicles and the state of the tunnel will be kept by transmitting information from the machinery and the drone to the Digital Twin and to specific Artificial Intelligence applications to monitor the progress of the work and the emissions of the machines.



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The main **workflow** with the detailed steps is as follows:

1. User access to DT interface to check the scheduled program of the “tunnel construction” for that day. Provide with a “general” computer at the entrance of the tunnel.
2. T4.1 (led by ITA) activates drone to perform an initial 3D – lidar scan of the tunnel prior to the operations.
3. Drone process captured information, update in DT the cloud point, send this 3D map to AWL (machine-to-machine communication always takes place without the DT as an intermediary, to avoid possible slowdowns or loss of data during the physical operation). 3D point cloud is analyzed in DT to confirm the operation schedule.
4. During processing of 3, debris is disposed inside the tunnel to simulate the detonation.
5. Once 3D models are ready (DT and AWL), smoke generator is activated.
6. AWL communicate to DT (T4.1) is ready to perform the activity, and T4.1 send commands to AWL to start operation once everything is ready (3D maps loaded into AWL, smoke device ready, debris is ready).
7. Drone and AWL access, autonomously, inside the tunnel (to be confirmed transit analysis for obstacles). Drone performs 3D scan and pass to AWL directly: NOT to DT in this step as previously mentioned. The goal is to update the AWL trajectory during their movement to the front of excavation.
8. AWL reaches front of excavation and perform loading of debris. Once AWL is full of debris, it will reverse to the external of the tunnel and unload debris to a dumper placed at the entrance of the tunnel (loading of dumper initially is performed outside the tunnel because tunnel dimensions does not allow AWL to maneuver – to be confirmed by AWL partners if can be done at the internal junction).
9. Repeat steps 7-8 until debris removed.
10. During the activities of AWL, AWL embedded sensors update tunnel map in collaboration with drone; once step 9 is finished, update “finished” map of tunnel into DT with the final 3D Lidar map. IoT data from AWL, drone or installed sensors inside the tunnel (as environmental) are sent “live” to DT. Machines. Live data examples are speed, position, orientation, etc.
11. DT databases have collected all the live data during activities, and updated 3D map of “initial” and “finished” tunnel -> perform, “off-line”, KPIs analysis, metrics, etc.
12. Repeat cycle next day.

The main workflow involves accessing the Digital Twin interface to check the scheduled program for tunnel construction, collecting real-time data from sensors and drones, monitoring progress and detecting anomalies, sending instructions to machinery vehicles, receiving status updates from them, and collaborating with other stakeholders. Based on this workflow, we have identified the following user stories (see Table 2):



EPICS	AS A	I WANT	SO THAT
Collaboration between stakeholders to ensure project success	Design team	To collaborate with other stakeholders and share design files in real-time using cloud-based tools	I can ensure that all design changes are communicated effectively and implemented correctly
Real-time monitoring and analysis of tunnel construction progress	Drone pilot	To obtain a 3D map of the tunnel construction site using drones equipped with sensors and cameras	I can provide accurate data to the Digital Twin platform for analysis and monitoring
Integration with existing systems and technologies to streamline processes	DT manager	To maintain the Digital Twin platform and ensure that it is up to date with real-time data from sensors installed in the tunnel	I can provide accurate insights to project leaders and other stakeholders
Increased efficiency and productivity through the use of real-time data and analytics	Field worker	To access the Digital Twin interface to check the scheduled program of the "tunnel construction" for that day provided with a "general" computer at the entrance of the tunnel.	I can plan my workday accordingly and ensure that I am working on the right tasks at the right time
Increased efficiency and productivity through the use of real-time data and analytics	Project leader	To monitor progress and identify potential issues in real-time using sensors installed in the tunnel as well as receive alerts when certain thresholds are exceeded, or anomalies detected.	I can make informed decisions and take corrective actions to keep the project on track
Increased efficiency and productivity through the use of real-time data and analytics	Project owner	To have access to a centralized platform that provides real-time updates on project progress costs risks as well as receive alerts when certain thresholds are exceeded, or anomalies detected.	I can make informed decisions about resource allocation budgeting risk management maintenance planning based on accurate data
Real-time monitoring and analysis of tunnel construction progress	Sensor installer	To easily install sensors in the tunnel without disrupting ongoing construction activities or compromising safety standards using communication protocols such as MQTT, REST, Sigfox or LoRaWan.	I can ensure that all necessary data is being collected without causing delays or safety hazards



EPICS	AS A	I WANT	SO THAT
Increased efficiency and productivity through the use of real-time data and analytics	Tunnel owner	To have access to a centralized platform that provides real-time updates on project progress costs risks and maintenance needs	I can ensure that the tunnel is being constructed and maintained according to my specifications and requirements
Improved safety for workers through the use of autonomous and teleoperated robotics	Wheel loader pilot (supervisor)	To receive real-time data on load capacity and obstacle detection from the AWL machine via CAN bus communication	I can operate safely and efficiently while carrying out my tasks
Environmental sustainability through the reduction of waste and emissions Continuous improvement through feedback loops and data-driven decision making	Data analyst	To access the Digital Twin platform and extract KPIs related to the productivity of the AWL, such as ratios between actual material removed and distance/time travelled by the loader, its consumption, and environmental metrics like CO2 emissions savings/fuel consumption.	I can provide accurate insights to project leaders and other stakeholders about the performance of the AWL and identify areas for improvement

Table 2. Tunnel Construction Epics and User Stories

Based on the main workflow, we have identified several user stories that guide the development process by providing specific goals for each stakeholder involved in the tunnel construction project. To further illustrate these user stories, we have created sequence diagrams in UML. The sequence diagram shows the interactions between different actors involved in a tunnel construction project, such as the User, Digital Twin Platform, Sensor and Drone Network, and Machinery Vehicles. The Tunnel Construction Sequence Diagram can be seen in Figure 6.



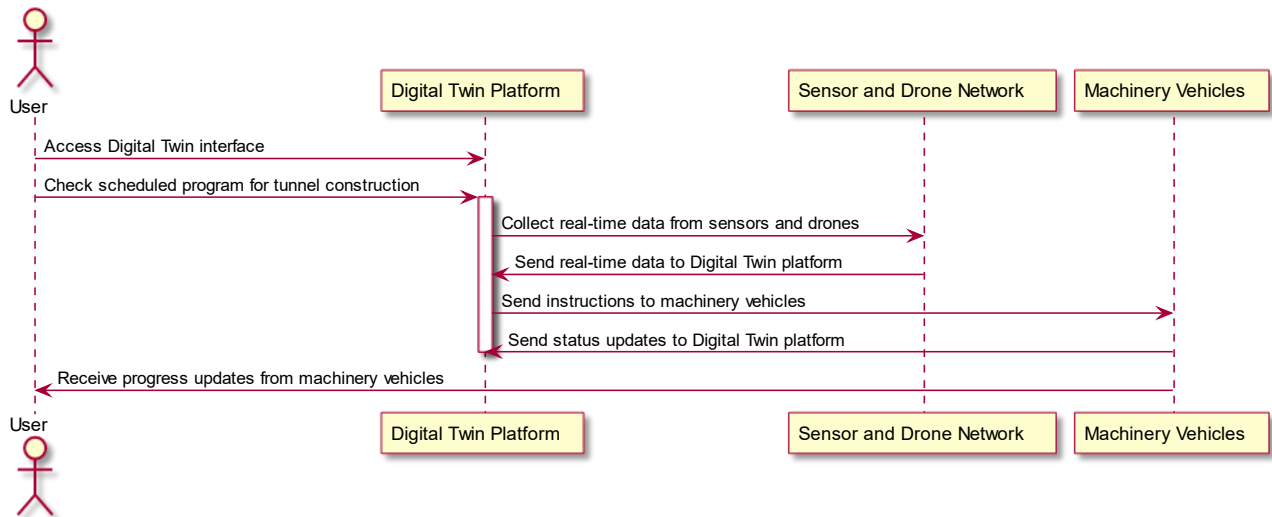


Figure 6. Tunnel Construction Sequence Diagram

The following BPMN diagram (see Figure 7) shows graphically the above workflow for this use case, with the DT being crucial for:

- Visualize the tunnel planning to prepare and start the daily tasks (a first 3D Cloud Point will be necessary to start this process, where the 3D point cloud is analyzed in DT to confirm the planning of the operation).
- Receive updated 3D Cloud Point from the UAV when possible: after a stop in the process (via an external PC with the drone outside the tunnel). DT to also keep track of obsolete 3D Cloud Point.
- Receive IoT data from autonomous machines.
- Establish the end of the daily tasks and obtain the KPIs of the process with the collected information.



[D3.1: Digital Twin Design and Architecture]

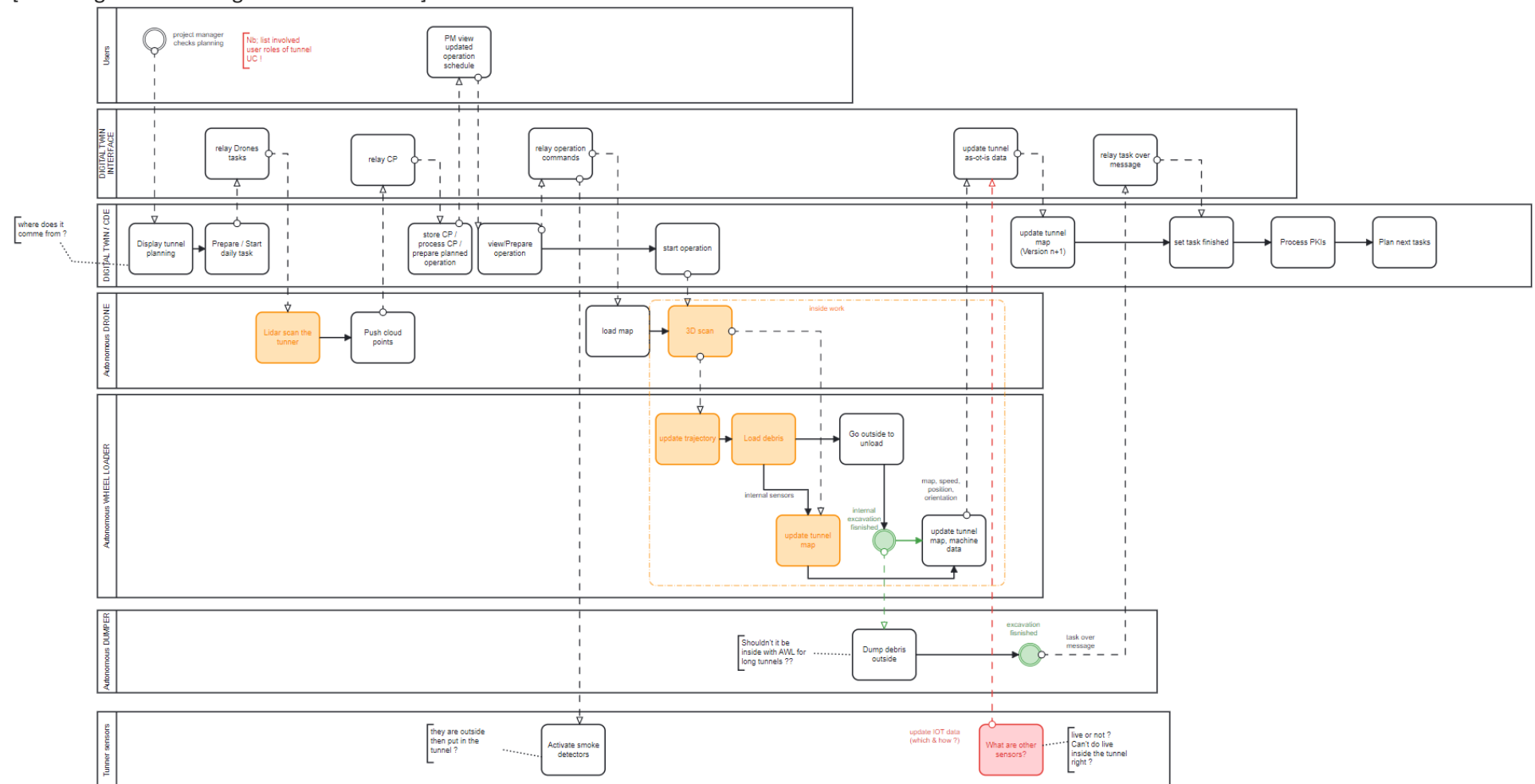


Figure 7. Tunnel Construction BPMN

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement N° 101058548.

The main **consortium's partners roles** of this case study can be summarized as follows:

- ACCIONA as Use Case leader and End User. Developers of Asset Tracking System platform.
- CSTB to provide interface T4.1 (in collaboration with ITA, to send and receive commands) and DT interface, able to show live data of machines, 3D point-clouds and schedule program of tunnel construction.
- TEC to provide operative database, data integration from autonomous machinery (mechanisms to be used by the autonomous machines to feed data to the DT data lake).
- DTU to perform off-line productivity analysis from cloud points comparison (initial and final) and perform KPIs obtention and metrics from data stored during use case (in terms of productivity & environmental – not safety in this case as no humans are present inside the tunnel).
- ITA: To provide with the Autonomous wheel loader and perform loading/unloading of debris in collaboration with a dumper.
- FADA: To 3D scan the tunnel sections using LIDAR.

In relation to the **hardware**, the crucial element of this case study is the AWL. This machine has Wi-Fi capability for remote control 1000 - 2000 meters deep in a tunnel and can measure the load it is carrying. It has 360° cameras for teleoperation and LIDAR sensors for obstacle detection, as well as GNSS for precise positioning. The AWL has a CAN bus for data collection as well as a communication cabin (data transmission process to the DT to be adapted by HIDROMEK). Different available networks may be considered depending on the availability/deployment capacity on site. Regarding **software**, the data platform will be assembled by TECNALIA (as per details in point 5) to accept data received mainly through MQTT and REST protocols. In relation to the drone, which will communicate machine-to-machine with the AWL without passing through the DT, the information collected for the DT will be a point cloud captured by LIDAR, which will be processed by the drone or from the central computer before being sent to the DT after the work has stopped. CSTB shall enable the display of cloud points (latest and historical) with proprietary software or free tools in the DT interface. A simplification of the process, showing with icons the main BTs and the moments of information exchange to the cloud (the functional unit is the interval in which KPI variations are studied), would be the following (between each drilling and blasting cycle). The Tunnel Construction Simplified Workflow can be observed in Figure 8.



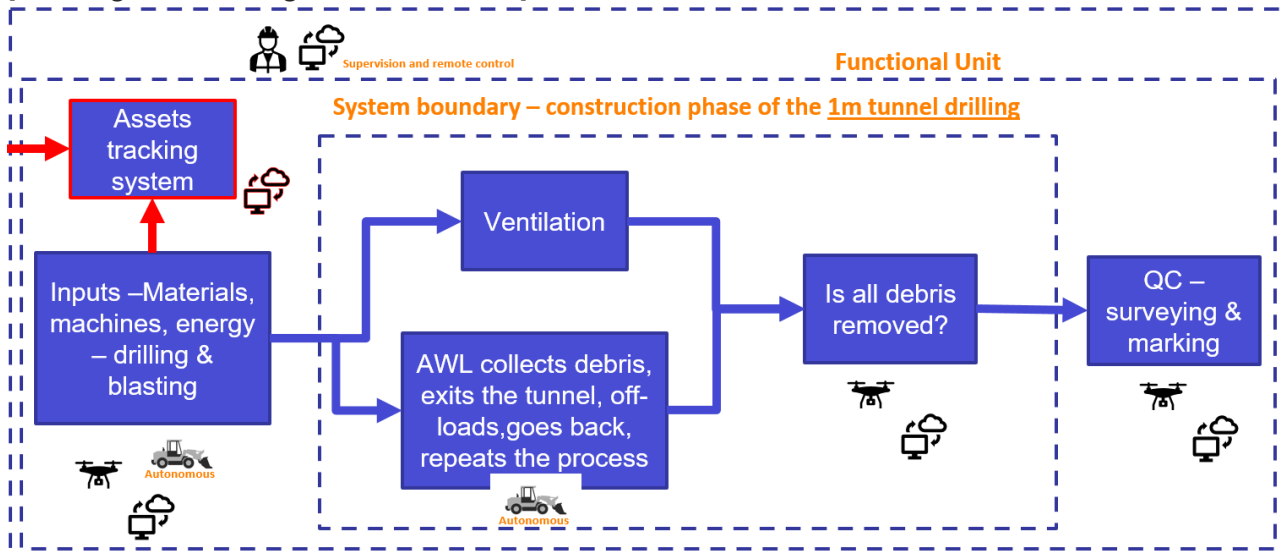


Figure 8. Tunnel Construction Simplified Workflow

The main **KPIs** will focus on the productivity of the AWL, through ratios between the actual material removed and the distance and time travelled by the loader and dumper, its consumption, and others. Environmental metrics (CO₂ emissions savings / fuel consumption...) will also be extracted (others will also be studied according to the next table, but not coming directly from the machines). The DT will collect all data from the AWL live during its activities, but the 3D job status map is only updated periodically once the job is completed and the drone can transfer this data to the central computer outside the tunnel. Then, from the "initial" and "final" status of the work performed and the AWL data, KPIs are extracted offline as a batch job. Finally, a comparison of conventional vs. new tunnel excavation cycle will be of interest (focusing on CO₂ reduction and increased efficiency). The table of KPIs identified can be found in the KPIs deliverables D2.3 – LCA/LCC KPIs and D2.4 – Workers KPIs.

Road Construction

In this use case, BEEYONDERS proposes an improvement of the earthmoving operation by using autonomous machines to reduce CO₂ emissions through route optimization. That is, machine operators will not drive along the best possible trajectories or in the most efficient driving mode in terms of productivity and emissions, because they are human drivers not directed by optimized algorithms. Smart wearables will also be included to monitor the proximity of machines to workers, as well as information gathered from other sensors installed on the road. An example (see Figure 9 for illustration purposes only) of visualization of trajectory data on the general map and working areas would be the following idea:



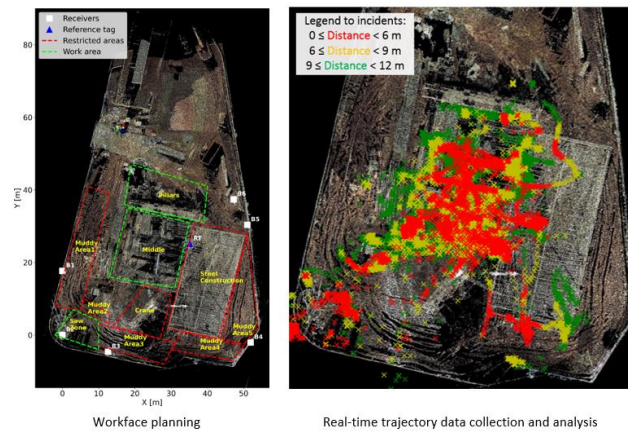


Figure 9. Road Construction Visualization

The **workflow** with the detailed steps is as follows:

1. User access to DT interface to check the scheduled program of the “road construction” for that day. Provide with a “general” computer at site.
2. T4.1 activates drone to perform an initial photogrammetry (prior to start the construction that day).
3. Drone process captured information, update in DT the initial surface photogrammetry.
4. DT defines the location for AWL task from initial 3D map and in concordance with construction schedule. Workers provided with smart wearables are located into defined task location, as well along the trajectory of the AWL.
5. 3D map is updated into AWL to perform the trajectory calculation from initial position (fixed) to task point (variable). Obstacle avoidance check.
6. AWL communicate to DT (T4.1) is ready to perform the activity, and T4.1 send commands to AWL to start operation once everything is ready.
7. AWL reaches task location and performs earthworks in collaboration with dumper. Dumper drops material into unloading area predefined from DT.
8. Workers perform other related earthworks activities around (to be defined, and not in the same AWL task location to simulate a real road construction process).
9. Repeat steps 6-7-8 until requested material volume is excavated.
10. During the activities of AWL, IoT data from AWL, SMW and installed sensors around the road (as environmental) are sent “live” to DT. Machines live data examples are speed, position, orientation, etc. SMW data examples are location, proximity alerts to AWL, muscular activity...
11. T4.1 activates drone to perform the final photogrammetry (at the end of the construction that day).
12. Photogrammetry from drone is uploaded to DT database.



13. DT database has collected all the live data during activities, and KPIs are obtained off-line to perform:
- Photogrammetry comparison to obtain productivity with material excavated volume
 - Trajectory record of autonomous machinery and workers are sent to ABM -> route optimization is performed, and safety of workers is analyzed.
 - Environmental analyses are performed to obtain related KPIs.
 - Workers KPIs are evaluated from data collected during use case.

14. Repeat cycle next day with optimized routes / optimized safety locations for workers.

Based on this workflow, we have identified the user stories in Table 3:

EPICS	AS A	I WANT	SO THAT
Develop a project timeline and budget Earthworks Planning	Design Team	To create an execution plan for the earthworks	I can ensure that the project is completed on time and within budget and the terrain is modified according to project specifications
Aerial Imaging	Drone pilot	To capture aerial images of the job site	To provide data for photorealistic recreations of the site
Real-time Monitoring	DT Manager	To monitor live data from machines and wearables on the job site	To ensure that tasks are being carried out efficiently and safely
Identify key data points to be collected and develop a sensor installation plan	Sensor Installer	To install sensors at various locations on the construction site	I can collect data on worker performance, machine usage and environmental factors
Develop an algorithm for optimizing routes based on real-time data	Autonomous Machinery Operator	To receive optimized routes for autonomous machinery and workers	To improve efficiency and reduce resource consumption
Develop a system for communicating route information to field workers in real-time	Field Worker	To receive optimized routes for autonomous machinery and workers	To ensure safety while working on site
Identify key environmental factors to be monitored	Environmental Analyst		To monitor the impact of the project on the environment
Develop a data analysis and machine learning plan	Data Scientist	To analyze data collected from systems installed on site	To provide insights to optimize project efficiency offline and in real-time regarding route optimization and safety of workers



EPICS	AS A	I WANT	SO THAT
Increased efficiency and productivity through the use of real-time data and analytics	Project Leader/Manager	To evaluate worker KPIs from data collected during use case to track progress and identify areas for improvement.	To make informed decisions about how to optimize the project in real-time.

Table 3. Road Construction Epics and User Stories

The sequence diagram is shown in the following Figure 10.

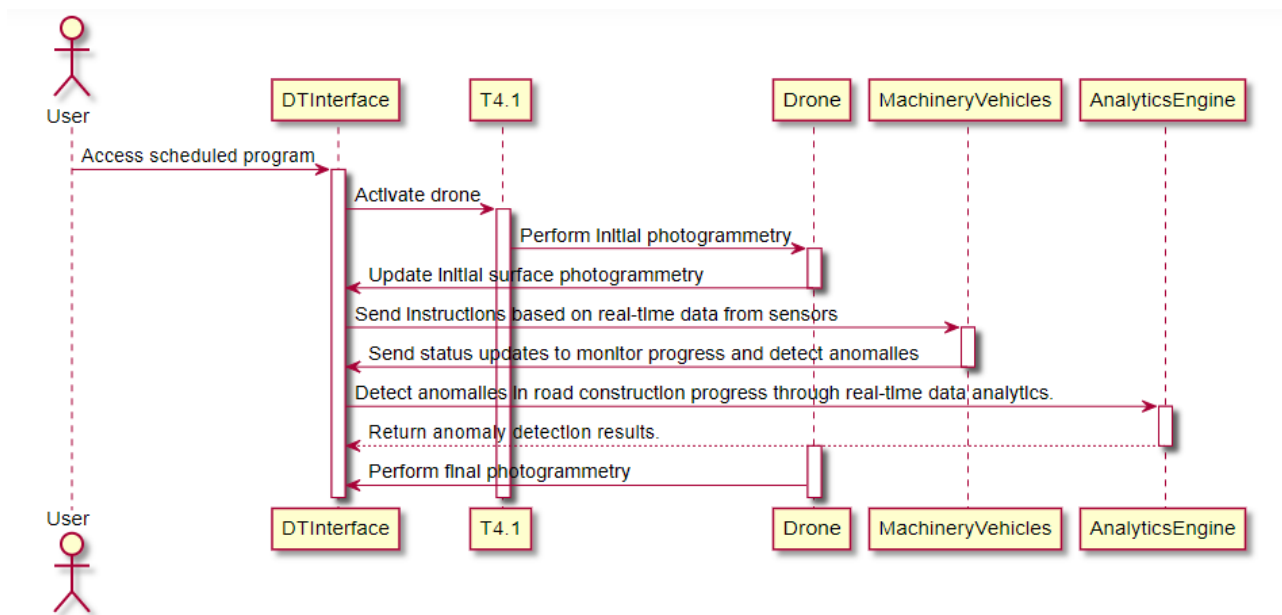


Figure 10. Road Construction Sequence Diagram

This sequence diagram shows the interaction between the user, the Digital Twin (DT) interface, T4.1, drones, machinery vehicles, and the analytics engine in the road construction use case. The user accesses the scheduled program through the DT interface and activates a drone to perform an initial photogrammetry before starting construction that day. The drone processes captured information and updates the DT with the initial surface photogrammetry. Real-time data is collected from sensors installed on machinery vehicles and other sources, and instructions are sent to machinery vehicles based on this data. Status updates are received from machinery vehicles to monitor progress and detect anomalies, which are detected through real-time data analytics by the analytics engine. Finally, anomaly detection results are returned to the DT interface for stakeholders to make informed decisions about the project's progress.



The following BPMN diagram (Figure 11) graphically shows the above workflow for this use case, with the DT being crucial to:

- Check the planned "road construction" schedule for the day and confirming the start of work.
- Store updated photogrammetry from the drone while also maintaining a historical record of previous maps
- Receive real time IoT data during AWL, SMW and sensor activities installed around the road
- Visualize this data on the photogrammetry map.
- Process (offline) and visualize KPIs.



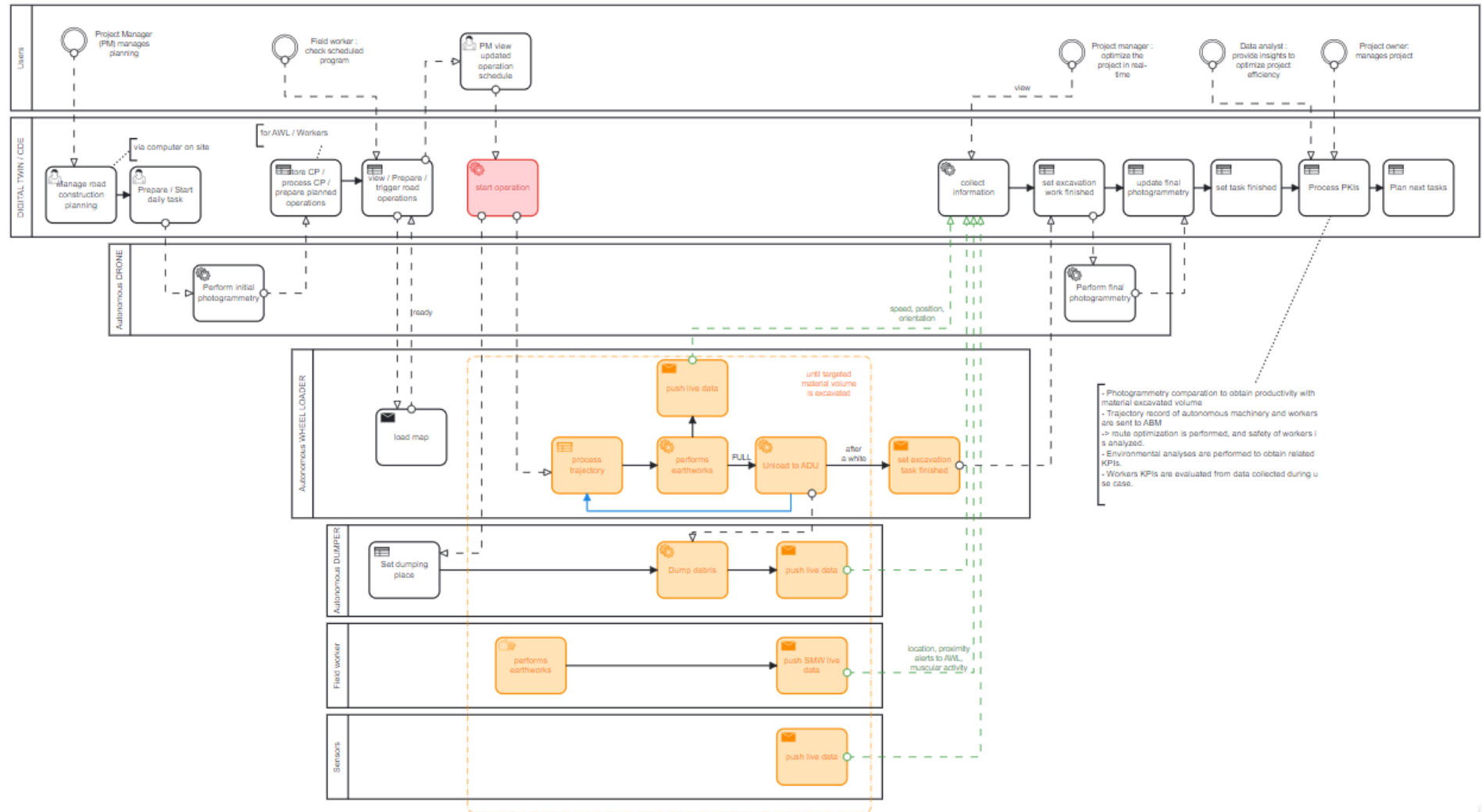


Figure 11. Road Construction BPMN

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement N° 101058548.

The main **consortium's partners roles** in this "road construction" case study are as follows:

ACCIONA as Case Study leader.

CSTB to provide interface T4.1 (in collaboration with ITA, to send and receive commands) and DT interface, able to show live data of machines, 3D point-clouds and schedule program of road construction.

TEC to provide operative database, data integration from autonomous machinery (mechanisms to be used by the autonomous machines to feed data to the DT data lake) and smart wearables. Allow SW with a dedicated slot to introduce / execute algorithms on the cloud computing premises.

DTU will perform an off-line productivity, safety, and environmental analysis from video-/photogrammetry, localization data, and engine data, respectively. KPIs will be measured by algorithms analyzing field data. Preprocessed data will be provided by other partners.

ITA to provide with the Autonomous wheel loader and perform loading/unloading of debris in collaboration with a dumper.

FADA to perform photogrammetry of the site before / after activities.

STAM / VTT to introduce in the use case Smart Wearables, providing DT with data measured from workers and VTT to perform a fatigue study based on data collected in DT. Tracking of location and proximity to AWL has to be sent to DT. ABM to perform off-line simulations to find optimal routes of AWL (based on data acquired during previous demonstration days) and safe working planning (analyse proximity interactions between workers and AWL).

In terms of **hardware**, the same AWL as in the previous use case will be used, while the drone will be an outdoor (larger) prototype. With the points recorded by it, photorealistic recreation (**software** to be defined by FADA) will be generated, being of interest the real-time tracking of machines (AWL adapted for sending to DT via REST or MQTT through the chosen network) and workers (wearables with IoT communication capability), as well as other data (sensors installed around the road), within a visualisation of the work area in the DT. As this is an open environment, it is assumed that a network (4G) and GNSS are available on site. Machines and drones connected P2P (IEEE 802.11ax), i.e. without direct mediation by the DT, to perform the work. The **software** integrated in the data platform and the digital twin is detailed, as far as possible at this stage, in points 5, 6 and 7, to cope with the required functionalities. A simplified process, using icons to show the main BTs involved and the moments of cloud data exchange (the functional unit is the interval in which KPI variations are studied), would be the following (see Figure 12):



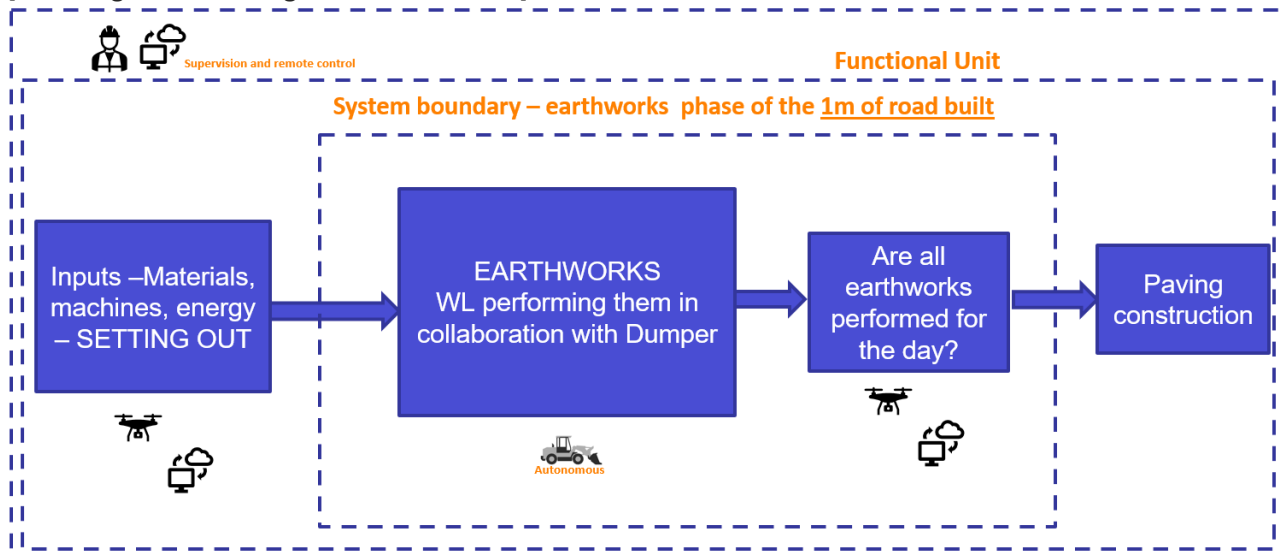


Figure 12. Road Construction simplified workflow

In terms of **KPIs** to be analysed, different classes are distinguished according to the previous case, being those initially contemplated (according to WP2 works as of the date of this document) for this road construction use case can be found in the KPIs deliverables D2.3 – LCA/LCC KPIs and D2.4 – Workers KPIs.

Building Construction

The building use case focuses on two main points, namely the estimation of the evolution of construction sites using information collected by UAVs and the use of exoskeletons and smart wearables to improve workers' conditions in terms of reduced effort and increased safety at work. The digital twin will be crucial to receive and visualize both sources of information, analyze it and extract the corresponding KPIs.

For the "Building Construction" use case it is proposed as a synthesized **workflow**:

1. DT interface for this use case is a BIM-based interface. The construction phase that will be the focus of this use case is the construction of the structural frame or the construction and finishing of internal wall partitioning, but the specific activities are to be confirmed depending on the site.
2. BIM model has the planification and working schedule of the building. According to the schedule, working areas for human workers are defined in DT, and scanning areas for drone as well. Environmental sensors to be installed in the working area (dust, CO₂, etc.).
3. Drone performs an initial LIDAR scan at the planned working area for the week / day (to be defined). Lidar point cloud is updated into DT database and processed.
4. Exoskeleton / Smart wearables perform their activities (to be defined) and two categories of datasets are involved:
 - Live data to be sent and show into DT (IoT): Location of worker, current activity, environmental exposition, any easy to send muscular / postural activity.
 - Complex data that require an off-line analysis as muscular ergonomics, fatigue, etc. is sent and stored into DT database, and DT manages the data where required to perform the analysis / metrics, and once are performed are stored into DT to be checked by users.
5. According to the planned production (for that day or week, to be confirmed), once relevant units should be finished, drone performs a LIDAR scan to obtain the as-built point cloud in the working



[D3.1: Digital Twin Design and Architecture]

area. Obtained point cloud is updated into DT, where comparing initial and final point cloud, it is executed:

- Productivity check detecting presence or absence of elements (panels, walls) where according to schedule and BIM planning are installed.
 - Reflectivity analysis from LIDAR to detect surfaces and textures of materials (concrete, wood...).
6. Productivity check according to schedule / update if required. H&S, productivity, and economy KPIs and metrics on DT.

In terms of the main **consortium's partners roles** in this case study, it is summarized as follows:

ACCIONA as WP leader and FLOWTECH as Use Case responsible.

CSTB to provide DT BIM-based interface, able to show live data from Smart Wearables and Exoskeleton and schedule program of building construction.

TEC to provide operative database, data integration from drone, smart wearables and exoskeleton.

DTU will perform an off-line productivity, safety, and environmental analysis from LIDAR, localization data, and engine data, respectively. KPIs will be measured by algorithms analyzing field data. Preprocessed data will be provided by the BEEYONDER partners.

FADA: To perform LIDAR scan on the defined working areas.

STAM / VTT: To introduce in the use case Smart Wearables, providing DT with data measured from workers and VTT to perform a fatigue study based on data collected in DT.

IIT: To introduce in the use case Exoskeleton, providing DT with data measured from workers and compute complex ergonomics analysis.

This case study focuses on tracking wearable data for H&S, as well as tracking the progress of tasks from the point clouds collected by the drone, in this case the indoor model (smaller than the outdoor model). This drone, equipped with LIDAR scanner, as well as the wearables, equipped with an IoT system and safety functions that generate alarms if thresholds are exceeded (T^a, Humidity, TVOC, CO₂, Man-down, GPS, etc.), are the main devices in relation to the **hardware**, together with the Exoskeleton, but the latter will communicate and send data (current activity of the worker, muscular / postural activity, etc.) to the DT through the wearables system. In relation to the platform **software**, which is specified in general (points 5 and 6), some kind of point cloud contrast tool (e.g., Cloud Compare) will be needed to measure the change in areas or volumes of interest for the production. A linear scheme as simple as possible, showing with icons the main BTs and the times of information exchange to the cloud (the functional unit being the interval in which the variations of the KPIs are studied), would be (see Figure 13):



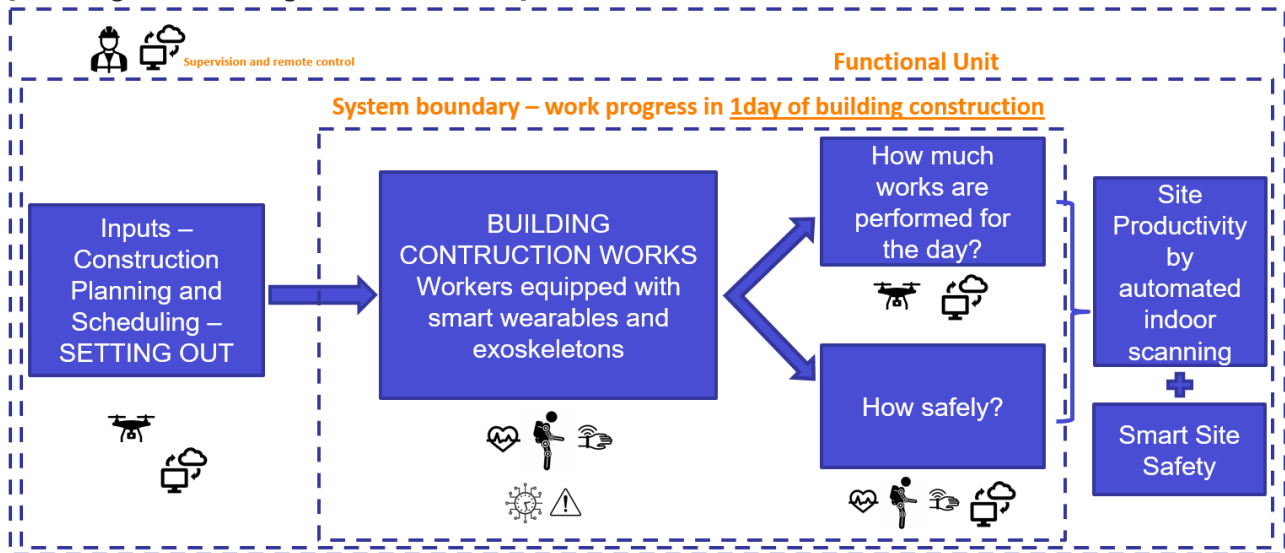


Figure 13. Building Construction simplified workflow

Based on this workflow, we have identified the following epics and user stories (see Table 4):

EPICS	AS A	I WANT	SO THAT
Project Planning	Design team	To have access to the BIM-based interface for the building construction project	I can design and plan the construction process effectively.
Aerial Scanning	Drone pilot	I want to build the 3D map of the construction site	I can provide accurate data for progress tracking and site analysis.
Real-time Monitoring	DT manager	I want to receive data from drones and sensors in real-time and update the BIM model accordingly	I can monitor progress, identify deviations from plans, and optimize resource allocation
Increased efficiency and productivity through the use of real-time data and analytics	Field worker	I want to have access to safety training and guidelines, as well as task assignments, schedules, productivity checks, and reflectivity analysis in real-time	I can work safely, efficiently, monitor my productivity levels, and improve my performance.
Increased efficiency and productivity through the use of real-time data and analytics	Project leader	I want to have real-time visibility into worker location, task progress, equipment status and safety data	I can make informed decisions to optimize resource allocation, improve worker safety, and ensure timely completion of tasks
Increased efficiency, safety and productivity	Project owner	I want to have access to data on construction progress,	I can make informed decisions about project timelines and



EPICS	AS A	I WANT	SO THAT
		quality, costs and environmental impact in real-time	budgets while ensuring compliance with regulations
Identify key data points to be collected and develop a sensor installation plan	Sensor installer	I want to install sensors at appropriate locations on the construction site according to specifications provided by DT manager or project leader	accurate data can be collected for progress tracking and site analysis
Develop a data analysis and machine learning plan	Data scientist	I want to use data captured from drones, wearables and exoskeletons to develop algorithms/models that allow field users perform their tasks efficiently and safely	field workers can benefit from advanced analytics tools to improve their performance while minimizing risks

Table 4. Building Construction Epics and User Stories

The sequence diagram is presented below (see Figure 14).

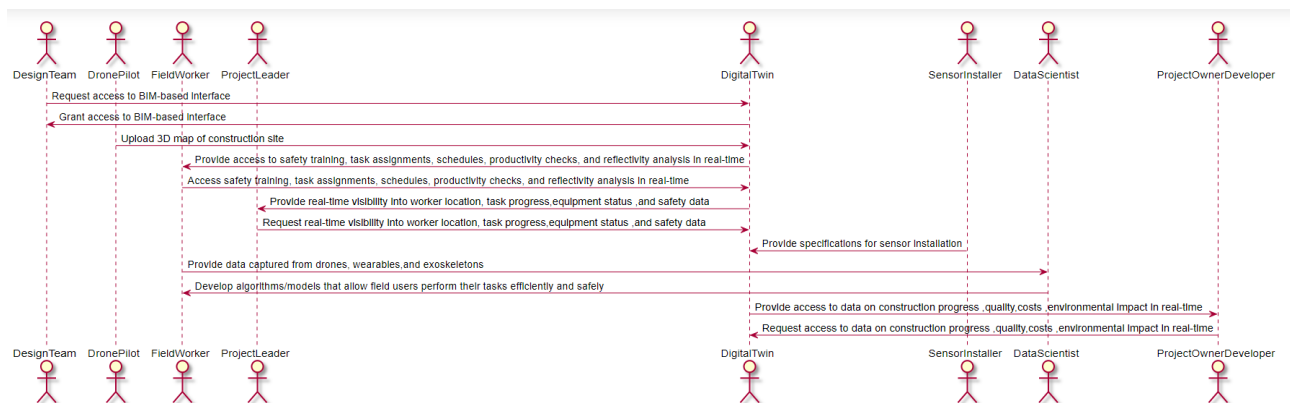


Figure 14. Building Construction Sequence Diagram

Regarding the KPIs to be analyzed, we distinguish the different classes seen in the previous cases (Social, Economic, Environmental and Technical), being those initially contemplated (according to WP2 works as of the date of this document) for this building construction use case can be found in the KPIs deliverables D2.3 – LCA/LCC KPIs and D2.4 – Workers KPIs.

The Building Construction BPMN is shown below (see Figure 15):



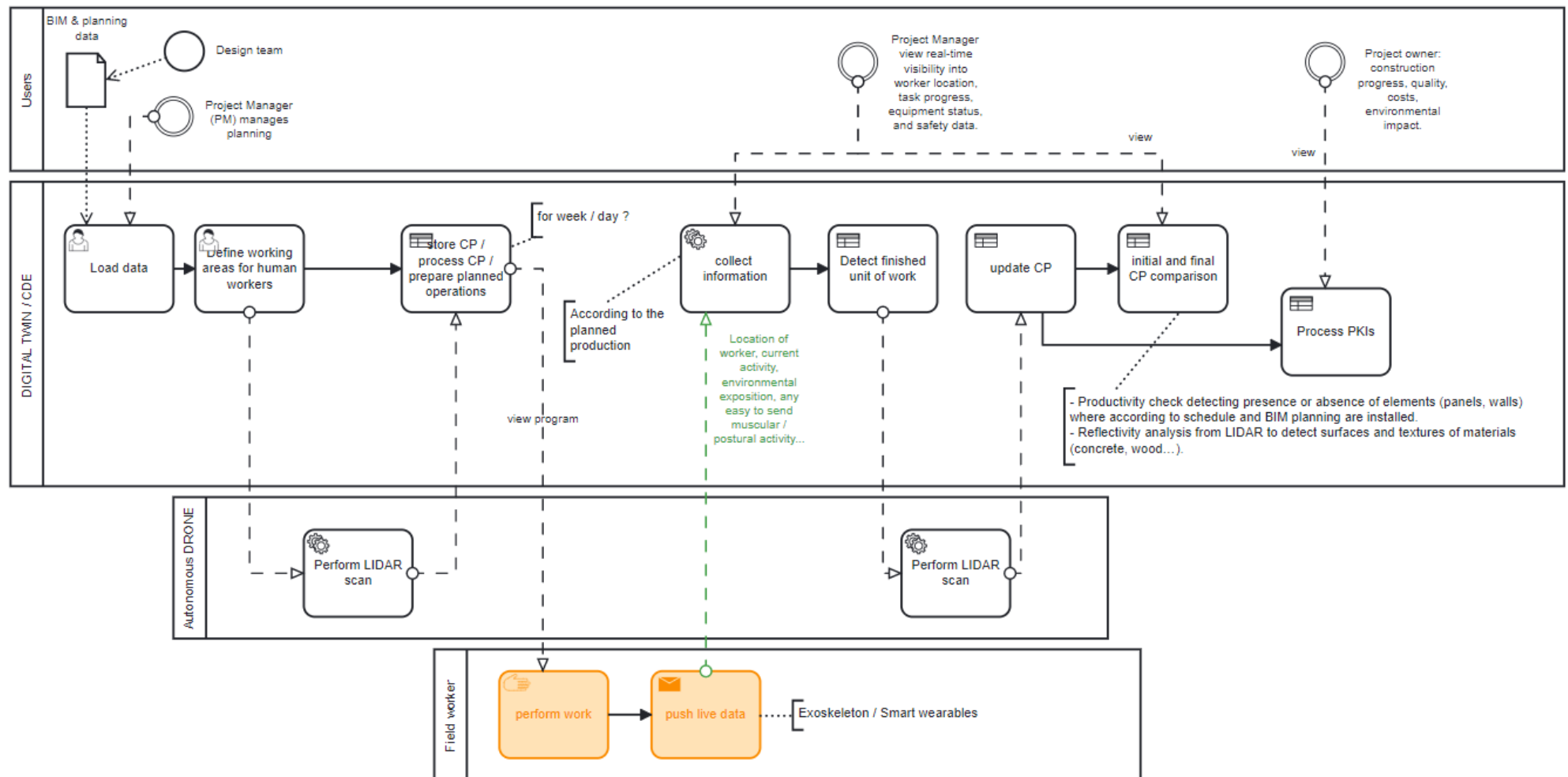


Figure 15. Building Construction BPMN

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement N° 101058548.

Maritime Construction

This case study focuses on the field of Additive Manufacturing for the construction of marine infrastructures (port caissons) with biocompatible mortars, in order to obtain structurally optimized designs to fulfill their resistant and environmental function, respecting marine biodiversity. Tecnia will also carry out a real-time monitoring of the structural conditions of the caisson, data that will be included together with its geometry in the DT, which in this case will play a minor role compared to the previous use cases.

The following series of steps are defined for this use case **workflow**:

1. Acciona & Holcim design the structure in terms of optimization of material volume of the caisson.
2. IoT deployment in material production factory. IoT data to be received in DT database and establish the route of the data to CAIDIO to perform their material production analysis calculations and optimization of material usage.
3. COBOD set up 3D concrete printer on the use case location dedicated space (or floating dock?)
4. Begin printing caisson sections with the biocompatibility mortars
5. Install reinforcement (if needed)
6. Apply a reef growth promoting coat once caisson is finished.
7. Connect sections between caissons. To be confirmed number of caissons to be installed.
8. Allow the caisson to cure (inland?)
9. Install wave harvesting equipment (optional) – (I do not see dedicated budget to do this, to be discussed)
10. 3D Scan of the finished caisson before submerging – DT interface can be 3D point cloud visualization or BIM-based. To be confirmed.
11. Install the caisson at designated location, and environmental sensors to be installed before submerging the caisson. To be defined types of environmental sensors by SEABOOST.
12. Establish the monitoring frequency and methodology to check biocompatibility of species on the structure. Receive environmental sensor data to DT database and calculate KPIs from data stored.

Based on this workflow, we have identified the following user stories and epics (see Table 5):

EPICS	AS A	I WANT	SO THAT
Real-time Project Monitoring	Port Authority	To receive regular updates on the progress of the construction project	I can ensure that the project is on track and meets our requirements
Real-time Data Access	Construction Manager	To have access to real-time data on the status of the construction site and equipment	I can make informed decisions about resource allocation and scheduling
Sensor Data Analysis	Structural Engineer	To be able to analyze data from sensors on the caisson structure in real-time	I can identify any potential issues or weaknesses in the structure and address them before they become a problem



EPICS	AS A	I WANT	SO THAT
Environmental Monitoring	Environmental Scientist	To receive regular updates on water quality and marine life around the construction site	I can monitor any potential impacts of the construction on the environment and take appropriate measures if necessary
Milestone Tracking	Project Manager (ACCIONA)	To be able to track progress against milestones and adjust schedules as needed	I can ensure that the project is completed on time and within budget
Sensor Data Retrieval	SEABOOST (IoT provider)	o receive data from environmental sensors installed around the caisson structure in real-time	we can monitor water quality, temperature, salinity, etc. around the structure for research purposes
Centralized Database Storage	DT database (Data storage provider)	To store all IoT sensor data collected from various sources	we can perform analysis, generate reports, and make informed decisions based on historical data
Material Production Analysis	CAIDIO (Data analysis provider)	To receive IoT sensor data from DT database for material production analysis calculations	we can optimize material usage during production
3D Point Cloud Visualization	BIM-based interface (DT interface provider)	To visualize 3D point cloud of finished caisson before submerging	we can verify structural integrity and identify any potential issues before submerging the caisson
Energy Harvesting	Wave harvesting equipment provider	To install wave harvesting equipment on the caisson structure (optional)	we can generate renewable energy from ocean waves
Reef growth promoting coat	Biocompatibility mortar provider	To apply a reef growth promoting coat on the caisson structure	we can promote marine life growth around the structure and improve its environmental impact

Table 5. Maritime Construction Epics and User Stories

The sequence diagram derived from the epics and user stories is as follows (see Figure 16):



[D3.1: Digital Twin Design and Architecture]

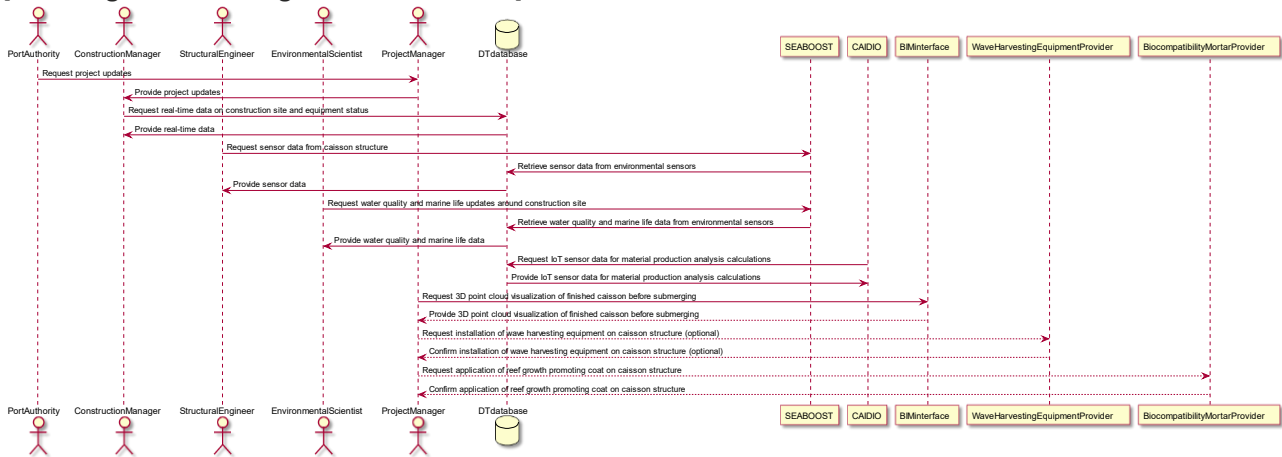


Figure 16. Maritime Construction Sequence Diagram

The main actors and their role in this "maritime construction" case study are:

ACCIONA to design the caisson structure with the optimised geometry.

COBOD to 3D-print the caisson at the port location.

CAIDIO to install and process IoT data monitoring from mortar production factory.

HOLCIM to study and define the optimised and functional bio-promoting and printable mortars that the caisson is going to be built and the reef growth promoting coat.

TEC to provide the DT database to receive data from environmental sensors and IoT production material sensors.

CSTB to provide with the dedicated interface in DT to visualize the caisson and the related data captured (sensors, KPIs, metrics, etc.)

SEABOOST to design the monitoring methodology to check biodiversity growth, define environmental sensors to be installed and design the reef growth promoting coat and required shapes.

The main hardware is the massive 3D printing technology that will be deployed. Diverse conditions during the construction process, along with the structural control of the caisson once printed, will be monitored with the corresponding sensing devices. A simplified illustration of the process of this use case, focused on the 3D printing of the caisson and its installation in a real port environment, can be seen below (see Figure 17):



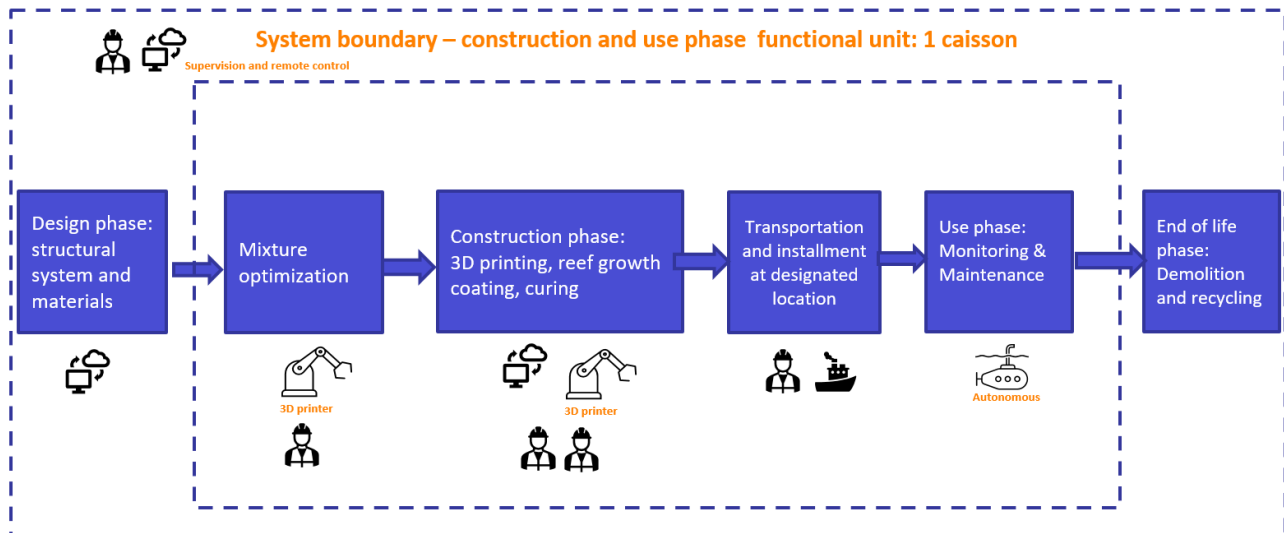


Figure 17. Maritime Construction simplified workflow

KPI selected for this maritime construction site, taking into account the social, economic, environmental and technical dimensions, can be found in the KPIs deliverables D2.3 – LCA/LCC KPIs and D2.4 – Workers KPIs.

The Maritime Construction BPMN is shown below (see Figure 15):



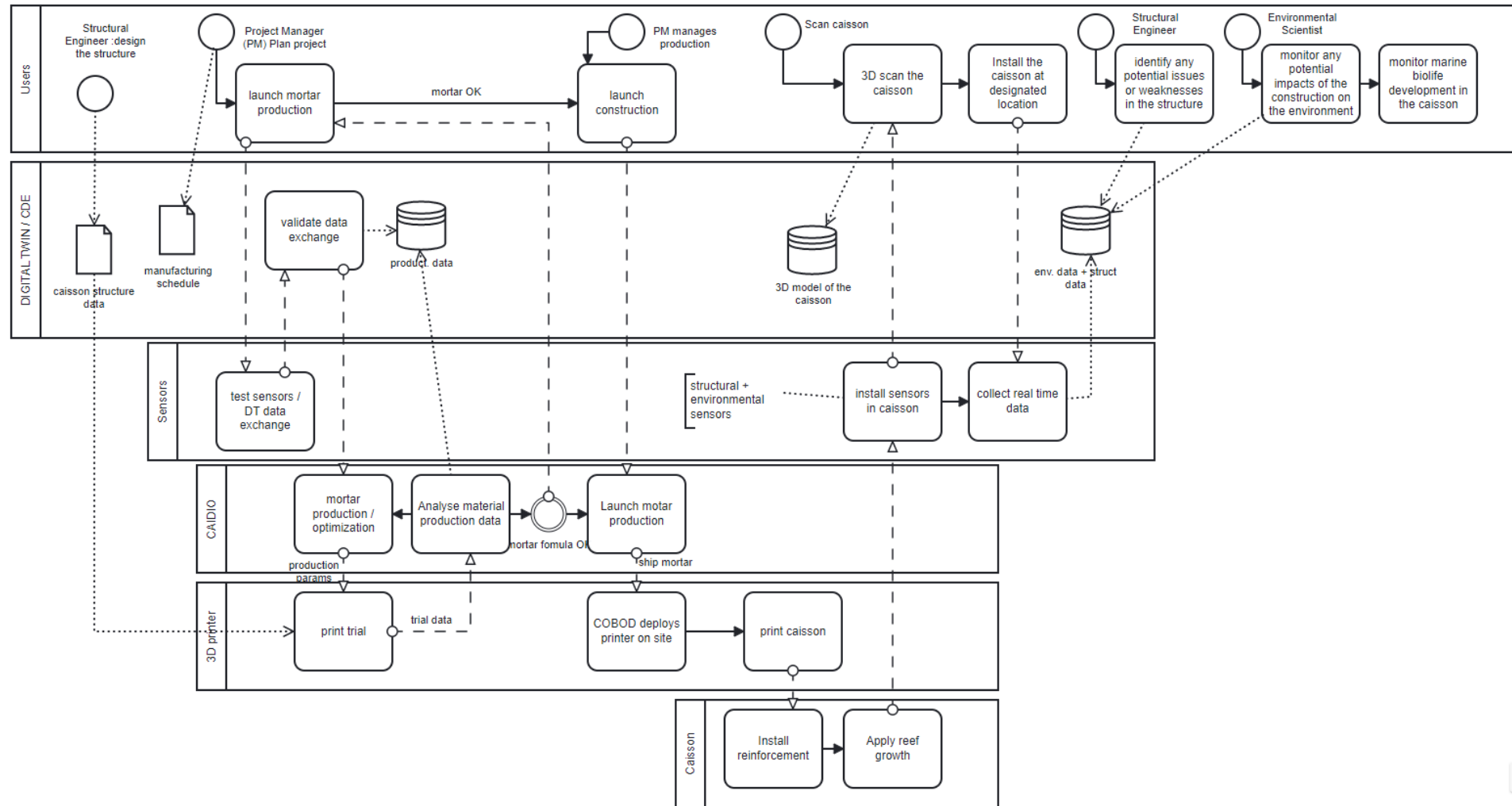


Figure 18. Maritime Construction BPMN

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement N° 101058548.

Maritime Construction (Japan)

In this case study, in collaboration with the Japanese machinery manufacturer Giken Ltd., an environmentally friendly DT of their push pile system will be developed. This will be done using data from Giken machinery installed at two demonstration sites, and also from the surrounding terrain, one at a test site in Japan and the other at a Dutch test site located in the port of Rotterdam.

For the "Maritime Construction" use case it is proposed as a synthesized **workflow**:

1. Together with Port of Rotterdam authorities, geotechnical data available is collected and deposited into DT database to feed and obtain a 3D model of the testing area the most detailed possible.
2. GIKEN machine is set up on site, and connection to the DT database is performed to allow DT receive data from machine or site computer. (To be defined)
3. Data collected by the machine during pile installation is stored into DT database, and from DT the data is formatted in a way it is converted into a file readable to INGEO geotechnical software (JSON scripts).
4. INGEO perform the geotechnical analysis and send it back to DT. To be defined the specific geotechnical analysis to be performed.
5. Results of analysis are shared in DT interface for GIKEN end-users.
6. Data stored in DT is used to make predictions in terms of estimation of ground capacity at points where no geotechnical tests exist, as well piling installation optimization in terms of results obtained / geotechnical analysis made. Economical / environmental KPIs obtention from optimization results.

The actors/roles in this use case with Japanese collaboration are:

ACCIONA as WP leader and INGEO as Use Case leader.

INGEO to communicate with Port of Rotterdam authorities and confirm availability of test site area, collecting information required to DT. To receive the script from DT with the updated geotechnical data from site and execute the geotechnical analysis, and send it back to DT. To execute geotechnical predictions from data stored in DT.

TEC to provide with operative database and datalake in DT, integrating the data received from GIKEN machine, developing the required API to send the data to INGEO software and formatting the information as required. To support INGEO executing geotechnical predictions from data stored in DT and providing KPIs from data received.

CSTB to provide DT interface able to show the 3D model of the test site and connected to DT database.

INFRAPLAN to analyze and compute LCA/LCC KPIs in this use case from results obtained with the pile length optimization (TBC the optimization is focused on this).

In this use case the process is focused, both in terms of hardware, software and purpose, on the Giken machine, so the DT will be a digital repository for tracking its operation and performance, i.e. there are no interrelationships to show with other BTs of the project in this use case.

Based on this workflow, we have identified the following user stories (Table 6):



EPICS	AS A	I WANT	SO THAT
Geotechnical collection management data and	Design team	To have access to geotechnical data of the testing area in Port of Rotterdam	I can design the pile system accordingly
	DT manager	To receive real-time data from GIKEN machine or site computer acting as a gateway	I can update the geological digital twin with accurate information
Sensor installation and data collection	Field worker	To be able to install sensors on site for collecting geotechnical data	I can contribute to the development of the digital twin
Prediction optimization and	Project leader	To have access to predictions based on estimation of ground capacity and piling installation optimization results	I can make informed decisions about project progress and resource allocation
Prediction optimization and	Project owner	To obtain economical and environmental KPIs from optimization results	I can evaluate the success of the project and its impact on the environment
Sensor installation and data collection	Sensor installer	To receive clear instructions on how to install sensors correctly	I can ensure accurate collection of geotechnical data

Table 6. Maritime Construction (Japan) Epics and User Stories



The sequence diagram for this use case is presented below (see Figure 19):

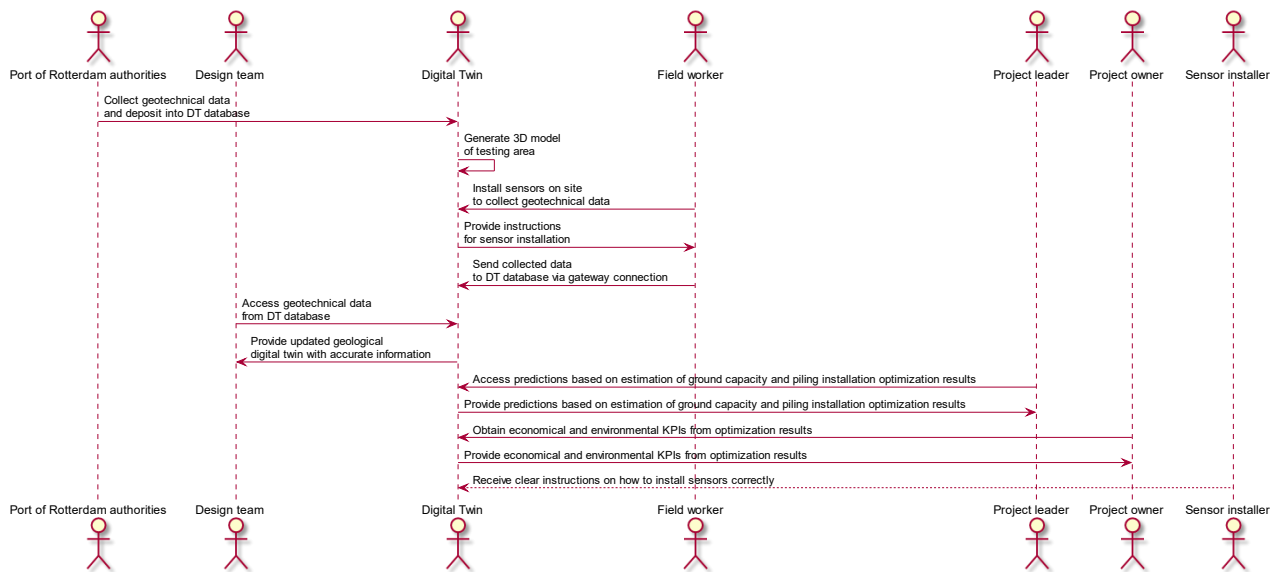


Figure 19. Maritime Construction (Japan) Sequence Diagram

The Japanese Maritime construction BPMN diagram is shown in the figure below:



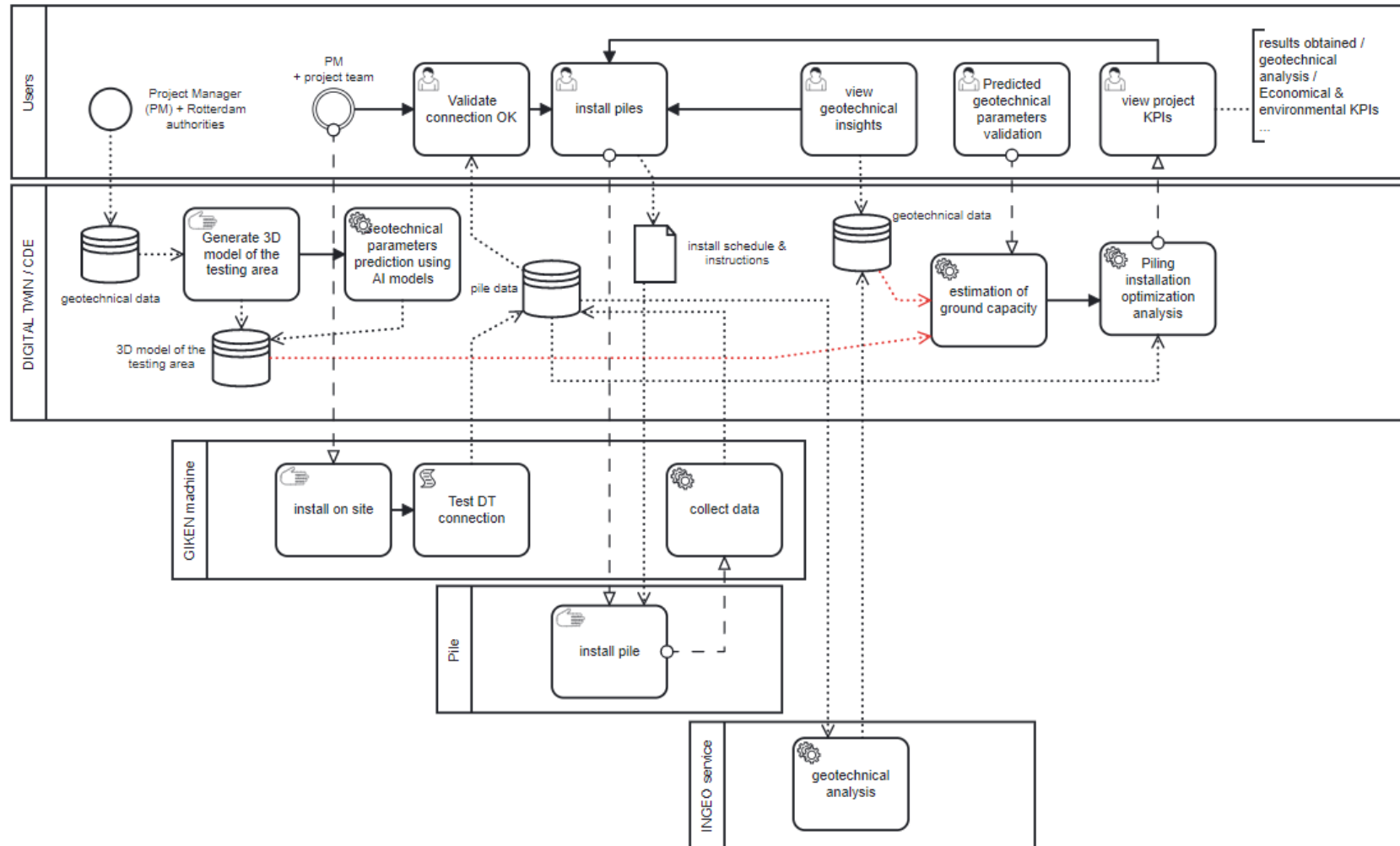


Figure 20. Japanese Maritime construction BPMN

The KPIs for the social, economic, environmental, and technical dimensions selected for this Japanese maritime construction use case can be found in the KPIs deliverables D2.3 – LCA/LCC KPIs and D2.4 – Workers KPIs.

Road Maintenance

The road maintenance case study is based on checking the reflectivity level of road signs and the condition of roadside vegetation, combining the capabilities of the outdoor UAV and an autonomous inspection vehicle.

For the "Road Maintenance" use case it is proposed as a synthesized **workflow**:

1. Once the road location is confirmed, manage permits to fly the drone over the road and to deploy the autonomous inspection vehicle.
2. Obtain the road elements database and provide it into DT database. Maintenance status will be updated here from results from drone / vehicle. Program the road sections to be inspected according to elements database and road manager schedule.
3. The drone perform fly over the section using LIDAR scan to detect vegetation on the sides of the road. Cloud point obtained with reflectivity information is updated into DT database. Reflectivity analysis from painting marks on road to be performed.
4. Autonomous inspection vehicle starts the reflectivity check of road marks and send results obtained to DT database.
5. From data obtained during use case:
 - a. Compare and validate reflectivity analysis of both devices (drone, vehicle).
 - b. Vegetation status identification as action required from LIDAR.

- KPIs obtention, in terms of resources optimised of avoiding human doing the inspection (for productivity, economy, workers, environmental...).

In terms of the main **project partners** and their role in this case study, it is summarized as follows:

ACCIONA as WP leader and AISCAT as Use Case leader.

TEC to provide operative database, data integration from drone and inspection vehicle, and allocate the road elements details into the database. To provide with the development and deployment of an Autonomous Inspection Vehicle able to perform reflectivity analysis of road marks.

CSTB to provide DT BIM-based interface to show the road section and related information of maintenance status.

FADA: To perform LIDAR scan on the defined road section to perform the vegetation check analysis, and reflectivity analysis.

AISCAT to provide with a road section that can fulfil the use case requirements.

In this road maintenance use case, the main hardware is the autonomous inspection vehicle itself and, again, the outdoor UAV, both with their internal software not related to the DT only to communicate the information collected during the road inspection by the communication protocols (of the possible ones



according to the architecture of the platform described below) that are determined to be the most appropriate depending on their availability on the road section finally selected. For simplicity, a one-line diagram of the use case process is shown below in Figure 21:

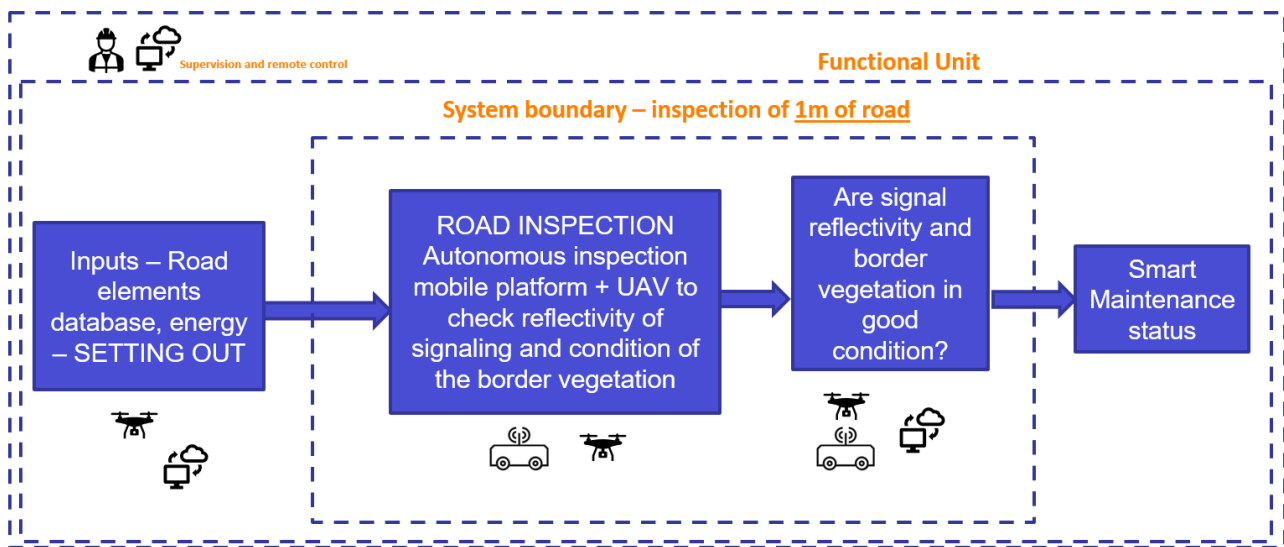


Figure 21. Road Maintenance simplified workflow

Based on this workflow, we have identified the following user stories (see Table 7):

EPICS	AS A	I WANT	SO THAT
Workflow Management	Road maintenance worker	To be able to perform inspections without having to physically visit every point on the road multiple times a day	I can save time and reduce safety risks for myself and other road users
Workflow Management	Road maintenance manager	To have real-time data on the status of road infrastructure elements such as traffic signals and vegetation growth	I can prioritize maintenance tasks based on actual needs and improve overall efficiency
Cost Optimization	Concessionaire owner	To minimize costs associated with road maintenance while still ensuring safe and reliable infrastructure for all users	I can maximize profits while maintaining high standards of service
Workflow Management	Project leader	To have a clear understanding of the workflow and responsibilities of each team member involved in the road maintenance project	I can ensure that the project is completed on time, within budget, and to the satisfaction of all stakeholders



EPICS	AS A	I WANT	SO THAT
Workflow Management	Legislator or policy maker	To receive data-driven insights into how to improve maintenance protocols for roads in my jurisdiction	I can make informed decisions that benefit both road users and taxpayers
Real-Time Data Collection and Analysis	Design team member	To be able to design a system that can accommodate autonomous robotics for road maintenance inspections	I can ensure that the system is scalable, efficient, and cost-effective
Autonomous Inspection Vehicle Development	Drone pilot	To be able to fly the drone over the road and deploy the autonomous inspection vehicle safely and efficiently	I can perform my job duties without endangering myself or others
Permit Management	DT manager	To be able to manage permits for flying drones over roads and deploying autonomous inspection vehicles in a timely manner	I can ensure that inspections are performed on schedule and without delays
Autonomous Inspection Vehicle Development	Field worker	To be able to use autonomous robotics to perform inspections (vegetation and reflectivity analysis) more efficiently and safely than traditional methods	I can reduce my workload, minimize safety risks, and improve overall job satisfaction
Autonomous Inspection Vehicle Development	Sensor installer	To be able to install sensors on infrastructure elements such as traffic signals in a way that is compatible with autonomous robotics for future inspections	I can ensure that data is collected accurately and efficiently for future analysis
Workflow Management	Project owner or sponsor	To have a clear understanding of the benefits of using autonomous robotics for road maintenance inspections, including cost savings, improved safety, and better data-driven decision-making capabilities	I can justify the investment in this technology to stakeholders and ensure its successful implementation

Table 7. Road Maintenance Epics and User Stories

The sequence diagram for the Road Maintenance Use Case is shown below in Figure 22:



This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement N° 101058548.

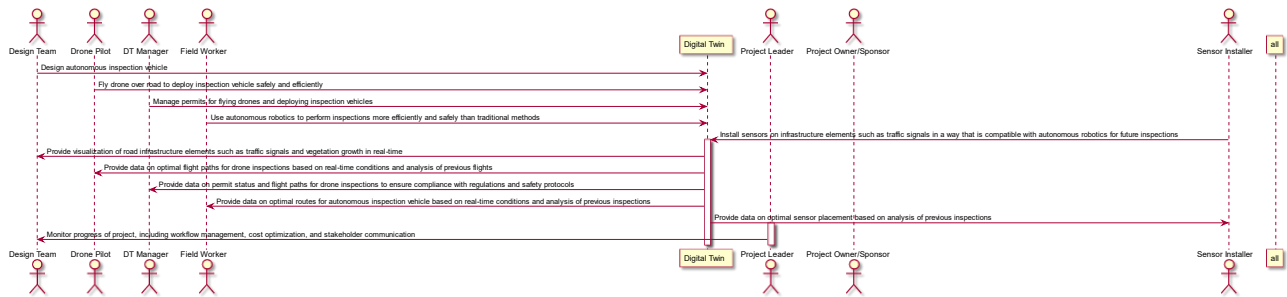


Figure 22. Road Maintenance Sequence Diagram

The Road Maintenance BPMN diagram is shown below in Figure 23:



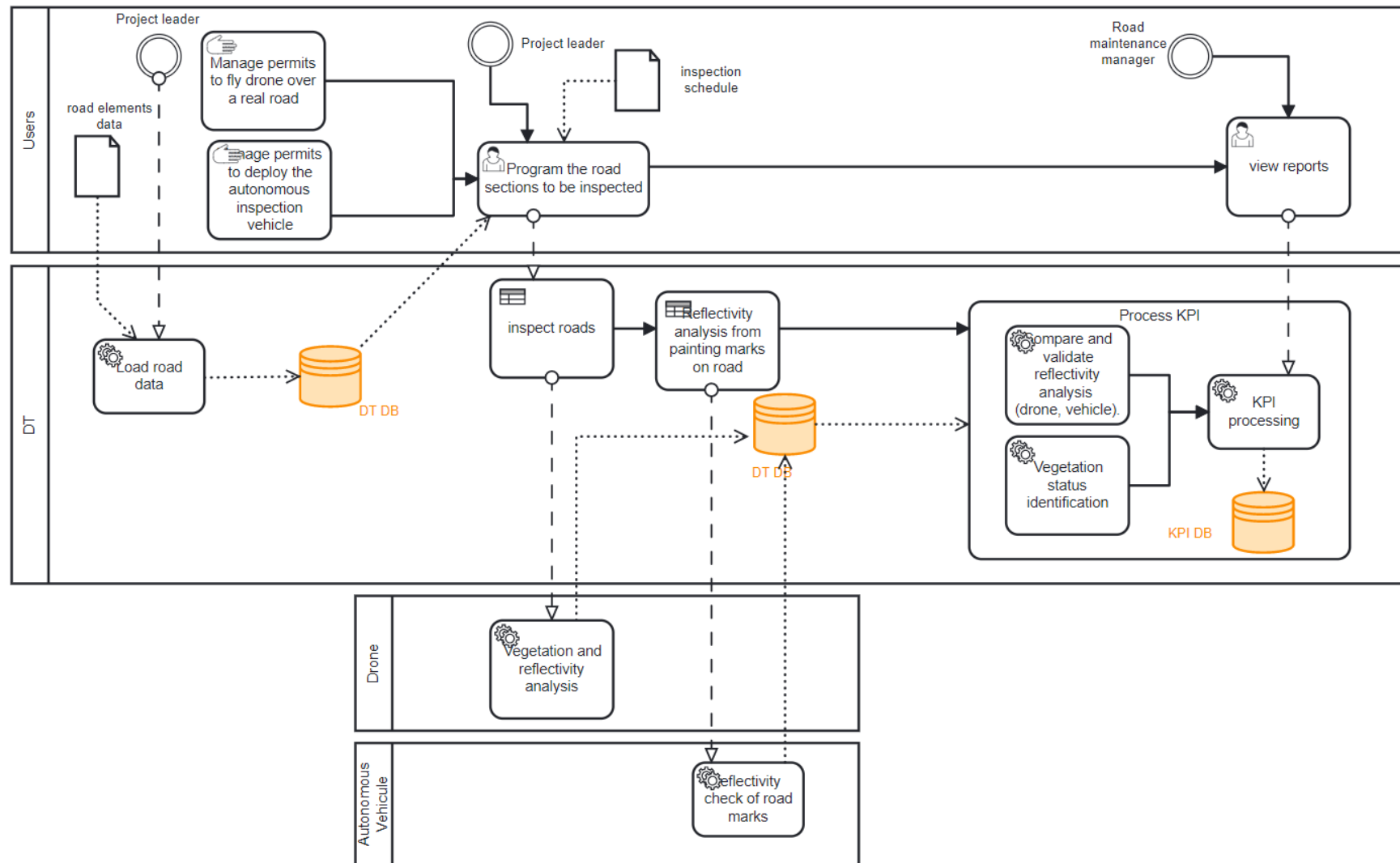


Figure 23. Road Maintenance BPMN

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement N° 101058548.

According to the current level of definition given in WP2, the KPIs for the case of road maintenance could be listed according to the KPIs deliverables D2.3 – LCA/LCC KPIs and D2.4 – Workers KPIs.

Common One-fit-all workflow

The 6 BEEYONDERS Use Cases were used as a starting point to generate a common one-fit-all workflow that can be used across different construction projects. This common workflow was designed to be flexible and adaptable, so that it could be customized to meet the specific needs of each project. Once the common workflow is established, it is broken down into epics and user stories.

The common one-fit-all workflow definition follows an agile development approach, which is a methodology that emphasizes flexibility and collaboration between different stakeholders involved in the project. This approach involves the generation of epics, user stories, and the definition of requirements along with a sequence diagram. Epics are high-level descriptions of features or functionality that are required for the system. They provide a broad overview of what needs to be done and help to identify key areas that require further analysis or development. User stories are more detailed descriptions of specific features or functionality that are required for the system. They provide a more granular view of what needs to be done and help to identify specific requirements that need to be met. The definition of requirements involves identifying specific criteria that must be met in order for the system to function as intended. This may involve identifying technical specifications, performance metrics, or other criteria that must be met in order for the system to meet its objectives. To finish with, a sequence diagram is a visual representation of how different components in the system interact with each other. It shows how data flows between different components and can help to identify potential bottlenecks or areas where improvements can be made.

By following an agile development approach and using epics, user stories, requirements definition along with sequence diagrams BEEYONDERS can ensure that all stakeholders have a clear understanding of what needs to be done and how different components in the system interact with each other. This approach also allows for greater flexibility and collaboration between different stakeholders, which can lead to better outcomes and more successful projects overall.

Finally, generic requirements were developed based on the epics and user stories. These requirements outline the functional and non-functional capabilities that the system need to have in order to support the common workflow. The requirements are designed to be flexible and adaptable, so that they can be customized for each construction project as needed.

CONSTRUCTION PROJECT MANAGEMENT USE CASE

A construction project management system is proposed that provides a Digital Twin (DT) interface for stakeholders involved in various types of construction projects. The DT interface allows users to access real-time data analytics, collaborate with each other, and make informed decisions based on accurate information about project progress. The system includes autonomous and teleoperated robotics, drones, and sensors installed on machinery vehicles and infrastructure to improve safety, efficiency, and accuracy during construction projects while reducing unproductive waits.

The system collects real-time data from sensors installed on roads, bridges, tunnels, machinery vehicles, and other sources. The drones are used to perform initial photogrammetry before starting work each day. Based on the drone inputs, AI algorithms select priority tasks to work on and send precise orders to the earthworks



[D3.1: Digital Twin Design and Architecture]

machinery with optimal trajectories in terms of distance. These machines carry out these tasks without the intervention of drivers through autonomous and teleoperated navigation are connected to the system to perform the work.

In terms of KPIs to be analyzed, four classes are distinguished:

- Productivity: Volume of material removed from AWL / time spent for operations / photogrammetry
- Safety: SMW interaction detection to AWL / Health & Safety (H&S) from worker measures
- Environmental: CO2 emissions savings / fuel consumption
- Technical: Focused on productivity / efficiency of the BTs, autonomy and reliability.

In a nutshell, this construction project management system provides a comprehensive platform for stakeholders involved in various types of construction projects to access real-time data analytics, collaborate with each other, and make informed decisions based on accurate information about project progress. By using autonomous and teleoperated robotics connected via P2P (IEEE 802.11ax), drones for initial photogrammetry, and sensors installed on machinery vehicles and infrastructure, the system improves safety, efficiency, and accuracy during construction projects while reducing unproductive waits.

Based on the previous use cases, we have identified the following epics and user stories:

Epic 1: Real-time Data Analytics and Collaboration

This epic focuses on providing construction project managers with real-time data analytics and collaboration tools to monitor progress and make informed decisions based on accurate information about project progress.

Epic 2: Efficient and Safe Execution of the Project

This epic focuses on ensuring efficient and safe execution of construction projects by providing site managers with tools to plan how tasks will be carried out on site.

Epic 3: Autonomous Navigation for Machinery Vehicles

This epic focuses on improving safety, efficiency, and accuracy during construction projects by providing machinery vehicle operators with autonomous navigation tools.

Epic 4: Accurate Data Collection

This epic focuses on collecting accurate data from drones, wearables, exoskeletons, autonomous machines and contextual sensors for use in various types of construction projects.

Epic 5: Data Management

This epic focuses on exploiting data across different types of construction projects. There are two types of analysis to be carried out with data:

- **Data analysis**, also known as historical analysis or descriptive analysis, is the process of examining, cleaning, transforming, and modelling data with the purpose of discovering useful information, drawing conclusions, and supporting decision-making. The goal of historical analysis is to identify



[D3.1: Digital Twin Design and Architecture]

patterns and relationships in historical data and to extract insights that can help us understand past events or phenomena

- **Machine learning** is a type of artificial intelligence that enables systems to automatically learn and improve from experience without being explicitly programmed. Machine learning algorithms are designed to learn from data and make predictions or decisions based on that learning. Machine learning involves training a model on historical data, and then using that model to predict future outcomes or behaviours. The goal of machine learning is to develop models that can learn and generalize from data, and that can make accurate predictions on new data that the model has never seen before

Epic 6: Cloud Data Service Management

This epic focuses on managing the cloud data service used by stakeholders across the organization and ensure that it is secure, reliable, and scalable. It also focuses on designing and implementing scalable data architectures that efficiently accommodate and exploit data from different construction projects.



The Epics and User Stories that depict the Common Workflow can be found in Table 8 below.

EPICS		AS A	I WANT	SO THAT
Real-time Analytics Collaboration	Data and	Construction Project Manager	To access real-time data analytics and collaborate with stakeholders involved in various types of construction projects	I can monitor progress in real-time and make informed decisions based on accurate information about project progress
Efficient Execution of the Project	and Safe the	Site Manager	To plan how tasks will be carried out on site, including machinery vehicles available, skilled workers, weather conditions, interference with other phases of the site, etc.	I can ensure efficient and safe execution of the project
Autonomous Navigation for Machinery Vehicles	for	Machinery Vehicle Operator	To receive precise orders from AI algorithms based on drone inputs for optimal trajectories in terms of distance to carry out tasks without intervention from drivers through autonomous and teleoperated navigation.	I can improve safety, efficiency, and accuracy during construction projects while reducing unproductive waits
Accurate Collection	Data	Drone Operator	To perform initial photogrammetry before starting work each day and final at the end of the day.	I can provide accurate data to stakeholders involved in various types of construction projects
Accurate Collection	Data	Environmental Specialist	To analyze CO2 emissions savings and fuel consumption data collected by the system.	I can assess the environmental impact of various types of construction projects and identify areas for improvement
		Health & Safety Officer	To analyze SMW interaction detection to AWL / Health & Safety (H&S) from worker measures data collected by the system.	I can ensure compliance with health and safety regulations during various types of construction projects
Data Management		Data Engineer	To create and maintain ETL pipelines so that data is properly ingested, transformed, and loaded into the datalake	stakeholders across the organization have access to accurate and up-to-date data



EPICS	AS A	I WANT	SO THAT
Data Management	Data Analyst	To explore and analyze large datasets	I can identify trends and insights that will help drive business decisions
	Data Scientist	To build machine learning models using large datasets	I can make accurate predictions about future trends and stakeholders anticipate potential issues or opportunities in various types of construction projects
Data Management	Machine Learning Engineer	To experiment with different algorithms and hyperparameters	I can optimize model performance of my machine learning models to assure they are accurate and reliable
Sensor installation and data collection	Sensor Installer	To install sensors in various types of construction projects and ensure they are properly calibrated and functioning.	accurate data can be collected and used to improve safety, efficiency, and accuracy during construction projects
Cloud Data Service Management	IT Administrator	To manage the cloud data service and ensure that it is secure, reliable, and scalable	stakeholders across the organization can access data analytics in real-time without interruption or security breaches
Workflow Management	Project Stakeholder	To access real-time data analytics and reports on project progress	I can make informed decisions based on accurate information about project progress
Cloud Data Service Management	Cloud Architect	To design and implement scalable data architectures	I have a flexible and adaptable system in place for managing data across different types of construction projects

Table 8. Common Workflow Epics and User Stories



The sequence diagram of the common workflow is presented in Figure 24 below:

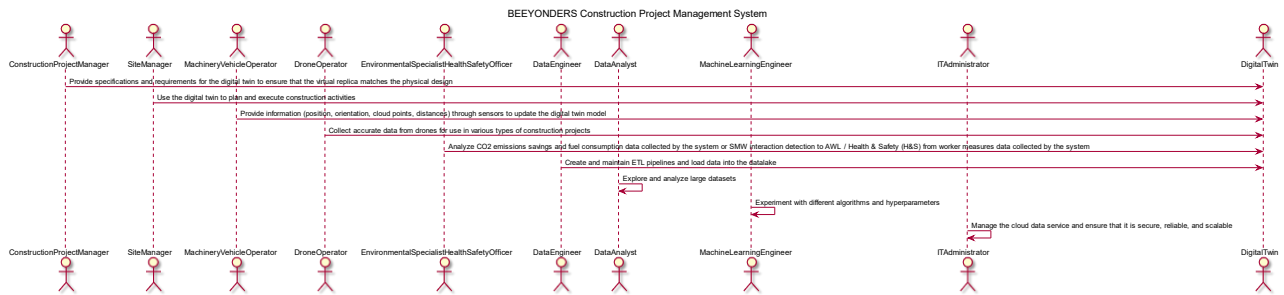


Figure 24. Common Workflow Sequence Diagram



Technical Requirements

Tunnel Construction Requirements

To achieve the goals in chapter 4, we have identified several functional requirements that must be met by the system. These include providing real-time monitoring of tunnel construction progress, autonomous and teleoperated robotics for machinery vehicles, collecting real-time data from sensors and drones, sending instructions to machinery vehicles based on real-time data, receiving status updates from machinery vehicles, detecting anomalies in tunnel construction progress, providing collaboration tools for stakeholders. Additionally, the Digital Twin platform should be able to collect real-time data from sensors installed in the tunnel and drones equipped with cameras and sensors, provide alerts when certain thresholds are exceeded or anomalies detected, extract KPIs related to productivity such as ratios between actual material removed and distance/time travelled by the loader and environmental metrics like CO2 emissions savings/fuel consumption. To ensure that these requirements are met efficiently and effectively we have identified several functional and non-functional requirements such as ensuring safety of workers through the use of autonomous and teleoperated robotics; improving efficiency and productivity through the use of real-time data analytics; ensuring environmental sustainability through reduction of waste emissions.

Functional Requirements

Functional requirements define what the system is supposed to do and focus on features and user requirements (see Table 9).

Functional Requirement No.	Functional Requirement Description
TCFR1	The system shall provide real-time monitoring of tunnel construction progress.
TCFR2	The system shall provide autonomous and teleoperated robotics for machinery vehicles.
TCFR3	The system shall collect real-time data from sensors and drones.
TCFR4	The system shall send instructions to machinery vehicles based on real-time data.
TCFR5	The system shall receive status updates from machinery vehicles.
TCFR6	The system shall detect anomalies in tunnel construction progress.
TCFR7	The platform should be able to provide a centralized interface for all stakeholders involved in a tunnel construction project (design team, drone pilot, DT manager, field worker, project leader, project owner, sensor installer, tunnel owner) to collaborate effectively and share design files in real-time using cloud-based tools.
TCFR8	The Digital Twin platform should be able to collect real-time data from sensors installed in the tunnel and drones equipped with cameras and sensors.
TCFR9	The platform should be able to provide alerts when certain thresholds are exceeded or anomalies detected.
TCFR10	The platform should be able to extract KPIs related to productivity, such as ratios between actual material removed and distance/time travelled by the loader, its consumption, and environmental metrics like CO2 emissions savings/fuel consumption.
TCFR11	The system shall be able to store and process large amounts of data in real-time.
TCFR12	The system shall be able to perform advanced analytics on collected data, such as machine learning algorithms for anomaly detection or predictive maintenance.



TCFR13	The system shall be able to integrate with other cloud services for seamless data ingestion and processing.

Table 9. Tunnel Construction Functional Requirements

Non-functional Requirements

Non-functional requirements describe how the system is supposed to behave in terms of its performance, reliability, security, and other aspects and define the qualities or characteristics of a system that are important to its overall performance but are not related to its specific functionality (see Table 10).

Non-functional Requirement No.	Non-functional Requirement Description
TCNFR1	The system shall ensure safety of workers through the use of autonomous and teleoperated robotics.
TCNFR2	The system shall improve efficiency and productivity through the use of real-time data and analytics.
TCNFR3	The system shall ensure environmental sustainability through the reduction of waste and emissions.
TCNFR4	The Digital Twin platform should be highly available and scalable to handle large amounts of data from multiple sources.
TCNFR5	The platform should have high performance and low latency to provide real-time insights into tunnel construction progress.
TCNFR6	The platform should have strong security measures in place to protect sensitive data from unauthorized access or breaches.
TCNFR7	The platform should be user-friendly and intuitive for all stakeholders involved in a tunnel construction project.
TCNFR8	The platform should comply with relevant regulations related to data privacy and security.

Table 10. Tunnel Construction Non-Functional Requirements

Road Construction Requirements

The list of functional and non-functional requirements for a road construction use case will help guide the development of a digital twin platform that can be used to monitor and manage all aspects of the project. These requirements will ensure that the platform meets the needs of all stakeholders involved in the project, from designers and engineers to field workers and project owners. By defining these requirements upfront, it is possible to avoid costly mistakes or delays later in the project. The requirements will serve as a roadmap for developers, ensuring that they are building a platform that meets all necessary specifications.



Functional Requirements

See Table 11.

Functional Requirement No.	Functional Requirement Description
RCFR1	Provide access to a Digital Twin interface for site managers to check the scheduled program of the road construction for that day
RCFR2	Activate a drone to perform an initial photogrammetry prior to starting construction each day
RCFR3	Process captured information from the drone and update the Digital Twin with the initial surface photogrammetry
RCFR4	Define the location for Autonomous Wheel Loader (AWL) tasks from initial 3D map and in concordance with construction schedule
RCFR5	Assign tasks to workers provided with smart wearables located into defined task locations, as well along the trajectory of the AWL.
RCFR6	Provide insights to optimize project efficiency offline and in real-time regarding route optimization and safety of workers
RCFR7	The system should collect real-time data from sensors installed on machinery vehicles and other sources.
RCFR8	The system should send instructions to machinery vehicles based on real-time data collected from sensors.
RCFR9	The system should receive status updates from machinery vehicles to monitor progress and detect anomalies.
RCFR10	The system should detect anomalies in road construction progress through real-time data analytics.
RCFR11	The system should provide collaboration tools for stakeholders to facilitate communication and coordination.

Table 11. Road Construction Functional Requirements

Non-functional Requirements

See Table 12.

Non-functional Requirement No.	Non-functional Requirement Description
RCNFR1	Machines and drones must be connected via P2P (IEEE 802.11ax) without direct mediation by DT to perform work.
RCNFR2	The software integrated in the data platform and Digital Twin must be detailed enough to cope with required functionalities
RCNFR3	Three classes of KPIs must be analyzed: productivity, quality, and safety.
RCNFR4	Performance: The system should be able to handle large amounts of real-time data from sensors and drones without significant delays or downtime.
RCNFR5	Reliability: The system should be reliable, with minimal errors or failures that could cause delays or safety issues during road construction projects.
RCNFR6	Security: The system should be secure, with appropriate measures in place to protect sensitive data and prevent unauthorized access or cyber attacks.



RCNFR7	Usability: The DT interface provided by the system should be user-friendly, intuitive, and easy to navigate for stakeholders involved in road construction projects.
RCNFR8	Scalability: The system should be scalable, able to handle increasing amounts of data as more road construction projects are added.

Table 12. Road Construction Non Functional Requirements

Building Construction Requirements

To ensure the successful implementation of a building construction project, it is crucial to define a set of functional and non-functional requirements. By defining these requirements, it is possible to avoid costly mistakes or delays later on in the project. In summary, creating a comprehensive list of functional and non-functional requirements is an essential step in developing a digital twin platform for building construction. These requirements will ensure that all stakeholders' needs are met throughout every stage of the project and help guide development efforts towards building an effective and efficient platform.

Functional Requirements

See Table 13.

Functional Requirement No.	Functional Requirement Description
BCFR1	Provide a BIM-based interface for the Design Team to access and update the central BIM model of the building.
BCFR2	Allow Drone Pilots to upload 3D maps of the construction site to the Digital Twin.
BCFR3	Provide Field Workers with real-time access to safety training, task assignments, schedules, productivity checks, and reflectivity analysis.
BCFR4	Provide Project Leaders with real-time visibility into worker location, task progress, equipment status, and safety data.
BCFR5	Allow Sensor Installers to receive specifications for sensor installation from the Digital Twin.
BCFR6	Allow Data Scientists to develop algorithms/models that allow field users perform their tasks efficiently and safely.
BCFR7	Provide Project Owner Developers with real-time access to data on construction progress, quality, costs, environmental impact.

Table 13. Building Construction Functional Requirements

Non-functional Requirements

See Table 14.

Non-functional Requirement No.	Non-functional Requirement Description
BCNFR1	The system should be secure and protect sensitive data from unauthorized access or modification.



BCNFR2	The system should be scalable and able to handle large amounts of data from multiple sources in real-time. The system should be reliable and available 24/7 with minimal downtime for maintenance or upgrades.
BCNFR3	The system should be user-friendly and easy to use for all actors involved in the building construction process.
BCNFR4	The system should comply with relevant regulations and standards related to building construction.

Table 14. Building Construction Non Functional Requirements

Maritime Construction Requirements

The list of functional and non-functional requirements for the maritime construction use case will help guide the development of a digital twin platform that can be used to monitor and manage all aspects of the project. These requirements will ensure that the platform meets the unique needs of maritime construction projects, which are subject to different demands than other types of construction projects due to their exposure to sea water chemical reactions and dynamic loads from waves.

Functional Requirements

See Table 15.

Functional Requirement No.	Functional Requirement Description
MCFR1	The system must be able to collect real-time data from environmental sensors installed around the caisson structure.
MCFR2	The system must be able to store all IoT sensor data collected from various sources in a centralized database.
MCFR3	The system must be able to provide real-time updates on the status of the construction site and equipment to the Construction Manager.
MCFR4	The system must be able to provide water quality and marine life updates around the construction site to the Environmental Scientist.
MCFR5	The system must be able to visualize 3D point cloud of finished caisson before submerging for verification purposes.
MCFR6	The system should provide a mechanism for testing and verifying the biocompatibility of the coating before it is applied to the structure.

Table 15. Maritime Construction Functional Requirements



Non-functional Requirements

See Table 16.

Non-functional Requirement No.	Non-functional Requirement Description
MCNFR1	The system must have high availability and reliability, as any downtime could result in delays or safety issues. The system must have high performance, as it needs to process large amounts of data in real-time.
MCNFR2	The system must have strong security measures in place to protect sensitive data from unauthorized access or breaches.
MCNFR3	The user interface should be intuitive and easy-to-use, as many different actors with varying levels of technical expertise will need to interact with the system.
MCNFR4	The system should comply with relevant environmental regulations and standards.

Table 16. Maritime Construction Non Functional Requirements

Maritime Construction Requirements (Japan)

Several functional and non functional requirements must be met to ensure the success of the project. These include the ability to receive geotechnical data from the GIKEN machine or site computer acting as a gateway or generate a 3D model of the testing area based on collected geotechnical data. In addition to these functional requirements, there are also several non-functional requirements that must be considered. These include performance, reliability, security, usability, and scalability.

The list of functional and non-functional requirements for this use case will help guide the development of a digital twin platform that can be used to monitor and manage all aspects of the project. These requirements will ensure that the platform meets the unique needs of maritime construction projects, which are subject to different demands than other types of construction projects due to their location, environmental conditions, and regulatory requirements.

Functional Requirements

See Table 17.

Functional Requirement No.	Functional Requirement Description
MCJFR1	The digital twin must be able to receive geotechnical data from the GIKEN machine or site computer acting as a gateway.
MCJFR2	The digital twin must be able to generate a 3D model of the testing area based on collected geotechnical data.
MCJFR3	The digital twin must be able to provide real-time designs of governing pile lengths using installation resistance and geotechnical data.
MCJFR4	The digital twin must be able to make predictions in terms of estimation of ground capacity at points where no geotechnical tests exist, as well piling installation optimization in terms of results obtained / geotechnical analysis made.



MCJFR5	The digital twin must be able to provide economical and environmental KPIs from optimization results.

Table 17. Maritime Construction (Japan) Functional Requirements

Non-functional Requirements

See Table 18.

Non-functional Requirement No.	Non-functional Requirement Description
MCJNFR1	Performance: The system should respond quickly to user requests and provide real-time updates on the status of the project.
MCJNFR2	Reliability: The system should be reliable and available at all times, with minimal downtime for maintenance or upgrades.
MCJNFR3	Security: The system should have appropriate security measures in place to protect sensitive data from unauthorized access or modification.
MCJNFR4	Usability: The system should be easy to use and navigate, with clear instructions for each user role.
MCJNFR5	Scalability: The system should be scalable to accommodate future growth and expansion of the project.

Table 18. Maritime Construction (Japan) Non Functional Requirements

Road Maintenance Requirements

The Road Maintenance Use Case presents unique challenges that require a specific set of functional and non-functional requirements to be defined for the digital twin platform. The list of functional and non-functional requirements for this use case will help guide the development of a digital twin platform that can be used to monitor and manage all aspects of road maintenance. These requirements will ensure that the platform meets the unique needs of road maintenance projects. By defining these requirements, it is possible to avoid costly mistakes or delays later on in the project. The requirements will serve as a roadmap for developers, ensuring that they are building a platform that meets all necessary specifications.

Functional Requirements

See Table 20.

Functional Requirement No.	Functional Requirement Description
RMFR1	The system shall be able to design an autonomous inspection vehicle that can perform reflectivity analysis of road marks.
RMFR2	The system shall be able to fly a drone over the road and to deploy the inspection vehicle safely and efficiently.
RMFR3	The system shall be able to manage permits for flying drones and deploying inspection vehicles.
RMFR4	The system shall be able to provide real-time data on road infrastructure elements such as traffic signals and vegetation growth.



RMFR5	The system shall be able to provide optimal flight paths for drone inspections based on real-time conditions and analysis of previous flights.
RMFR6	The system shall be able to provide data on permit status and flight paths for drone inspections to ensure compliance with regulations and safety protocols.
RMFR7	The system shall be able to provide optimal routes for autonomous inspection vehicles based on real-time conditions and analysis of previous inspections.
RMFR8	The system shall be able to provide data on optimal sensor placement based on analysis of previous inspections.

Table 19. Road Maintenance Functional Requirements

Non-functional Requirements

See Table 20.

Non-functional Requirement No.	Non-functional Requirement Description
RMNFR1	Performance: The system should respond quickly to user requests, with minimal latency or delay in providing real-time data or analysis results.
RMNFR2	Reliability: The system should operate reliably under different weather conditions, including adverse weather such as rain or snow.
RMNFR3	Security: The system should ensure that all data is transmitted securely, with appropriate encryption and access controls in place.
RMNFR4	Scalability: The system should be scalable, allowing it to handle large amounts of data from multiple sources without compromising performance or reliability.
RMNFR5	Usability: The user interface should be intuitive and easy-to-use, allowing different actors involved in road maintenance inspections to access the information they need quickly and easily.

Table 20. Road Maintenance Non Functional Requirements

Common Workflow Requirements

To ensure that the Common Workflow user stories and epics are met efficiently and effectively we have identified some technical requirements derived from Chapter 4.

1. The Digital Twin must be able to accurately represent the physical building or infrastructure
2. The Digital Twin must be able to receive and process data from various sources, such as sensors, drones, autonomous machines, wearables and exoskeletons
3. The Digital Twin must be able to provide real-time updates on the status of construction activities
4. The system must be able to generate reports and analytics based on data collected by the Digital Twin
5. The system must be able to provide a user-friendly interface for accessing and interacting with the Digital Twin
6. The system must be highly available and reliable, with minimal downtime or disruptions
7. The system must be scalable, able to handle large amounts of data and users as needed
8. The system must be secure, with appropriate measures in place to protect sensitive data



9. The system must have good performance, with fast response times for user requests
10. The system should have good usability, with an intuitive interface that is easy for users to navigate

These requirements were translated into formal functional and non-functional requirements in the sections below. Functional requirements describe what a system is supposed to do, while non-functional requirements describe how it is supposed to do it. Both types of requirements are important for developing systems that meet the needs of their users and perform effectively in their intended environment.

Functional Requirements

Functional requirements are the specific functions or features that a system or software must perform to meet the needs of its users. They describe what the system is supposed to do in terms of its intended behavior or functionality. Examples of functional requirements include: "The system shall allow users to create an account," or "The system shall calculate and display the total cost of items in a shopping cart". The functional requirements of the Common System are presented in Table 21.

Functional Requirement No.	Functional Requirement Description
FR1	The system must be able to create and maintain a virtual replica of the physical building or infrastructure
FR2	The system must be able to receive and process data from various sources, such as sensors and drones, autonomous machines, wearables and exoskeletons
FR3	The system must be able to provide real-time updates on the status of construction activities
FR4	The system must be able to generate reports and analytics based on data collected by the Digital Twin
FR5	The system must be able to provide a user-friendly interface for accessing and interacting with the Digital Twin
FR6	The system must be able to integrate with other construction management tools, such as BIM software and simulation software
FR7	The system must be able to track progress against project timelines and milestones
FR8	The system must be able to identify potential issues or delays in construction activities
FR9	The system must be able to provide recommendations for optimizing construction workflows
FR10	The system must be able to support collaboration between different stakeholders involved in a construction project, such as architects, engineers, contractors, and owners
FR11	The system must be able to manage permissions and access control for different users based on their roles and responsibilities
FR12	The system must be able to store historical data about construction projects for future reference or analysis
FR13	The system must be able to support multiple languages for global use cases
FR14	The digital twin should have an API that allows third-party applications or services to interact with it
FR15	Users should have the ability to customize their dashboard view
FR16	Users should have access to a library of pre-built templates for specific workflows
FR17	Users should have access to training materials or tutorials on how to use the platform
FR18	Users should have access to technical support if they encounter issues while using the platform



FR19	Users should have access to a knowledge base or FAQ section for common questions or issues
FR20	The system should be able to provide alerts or notifications to users based on specific events or triggers

Table 21. Common Workflow Functional Requirements

Non-functional Requirements

Non-functional requirements define the qualities or characteristics of a system that are important to its overall performance, but are not related to its specific functionality. Non-functional requirements describe how the system is supposed to behave in terms of its performance, reliability, security, and other aspects. Examples of non-functional requirements include: "The system must be able to handle 1000 simultaneous users," or "The system must provide a response time of less than 2 seconds for all user requests". The non-functional requirements of the Common System are presented in Table 22.

Non-functional Requirement No.	Non-functional Requirement Description
NFR1	The system must be highly available and reliable, with minimal downtime or disruptions
NFR2	The system must be scalable, able to handle large amounts of data and users as needed
NFR3	The system must be secure, with appropriate measures in place to protect sensitive data
NFR4	The system must have good performance, with fast response times for user requests
NFR5	The system should have good usability, with an intuitive interface that is easy for users to navigate
NFR6	The system must be accessible to users with disabilities, such as visual or hearing impairments
NFR7	The system must be compatible with different web browsers and devices
NFR8	The system must be able to handle concurrent user sessions without performance degradation
NFR9	The system must be able to handle large file uploads and downloads, such as high-resolution images or videos
NFR10	The system must have a backup and disaster recovery plan in place to ensure data is not lost in case of a failure or outage
NFR11	The system should have a high level of data accuracy and integrity, with appropriate validation checks in place
NFR12	The system should have a low error rate, with appropriate error handling mechanisms in place to prevent data loss or corruption
NFR13	The system should have good data privacy practices, with appropriate measures in place to protect user data from unauthorized access or disclosure
NFR14	The system should comply with relevant industry standards and regulations, such as GDPR or HIPAA
NFR15	The system should have good documentation that is up-to-date and easy to understand for users and developers alike
NFR16	The system should have good performance under load testing scenarios
NFR17	Users should be able to access the platform from anywhere at any time
NFR18	Users should be able to customize their notifications settings



NFR19	Users should be able to export their data from the platform if needed
NFR20	Users should be able to import their existing data into the platform if needed

Table 22. Common Workflow Non Functional Requirements



Modular Architecture Definition

What is intended with the Construction Digital Twin is to have a complete dynamic and virtual model of a physical building or infrastructure with a real-time reflection of the status and evolution of any activity that occurs in each of the different use cases defined in the project in order to provide a collaboration platform in terms of construction, operation and maintenance.

To create a construction digital twin, a robust architecture design is necessary. The architecture design encompasses the hardware, software, data, and networking components required to build, operate, and maintain the digital twin. To fulfil the scalability and interoperability requirements the architecture is organised through a layer model, in which each layer represents a specific set of technologies – according to their purpose – and that defines the communication across layers. It is a modular architecture that is grouped in the following levels: data source layer, acquisition layer, persistence layer, business layer and presentation layer.

Each of these layers is detailed in the Figure 25 below.

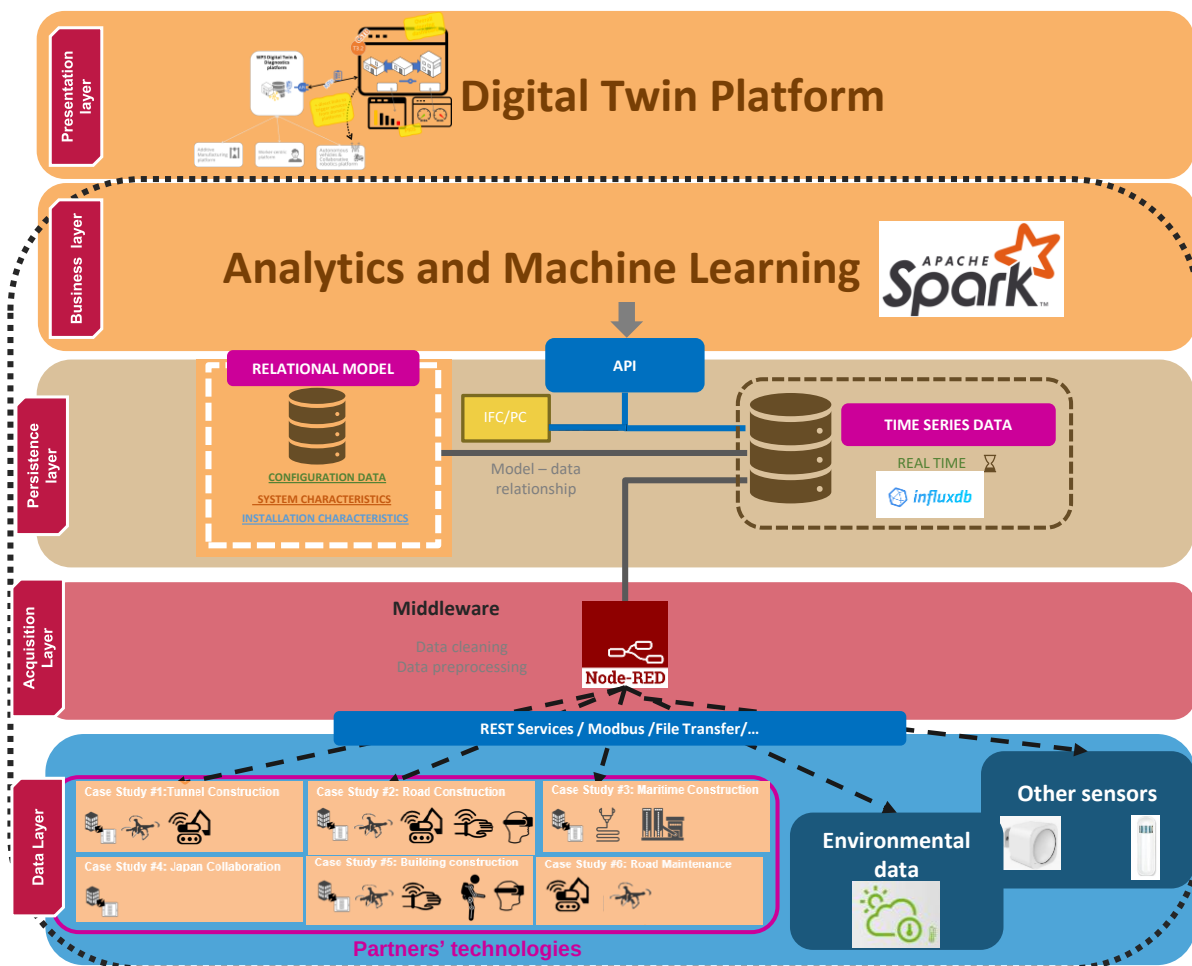


Figure 25. Digital Twin Conceptual Architecture



Data Source Layer

The layer includes those physical elements that either provide the system with information about the construction process of each of the use cases and the wellbeing and safety of workers, or those that must be controlled by the system (such as autonomous vehicles).

This layer (see Figure 26) includes the different systems contemplated in the BEEYONDERS project for each of the use cases, like autonomous and teleoperated robotics, drones, exoskeletons, wearables, additive manufacturing, as well as ambient sensors. That is, all the systems, elements, sensors and devices involved in the different use cases taking into account their different communication protocols.

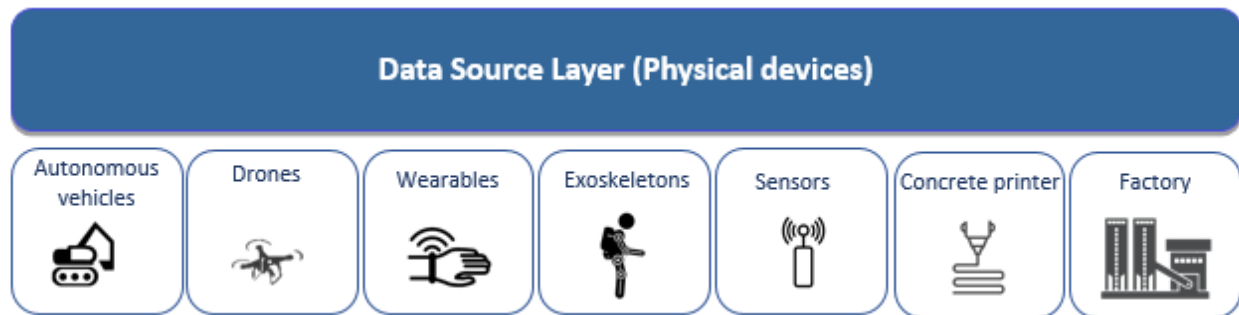


Figure 26. Digital Twin Data Source Layer

In order to monitor and control the different parameters of the systems that will be part of the use cases, it is necessary to establish a list of all existing technologies, with the measurements that can be monitored, as well as define their units and data acquisition time periods. The different categories of data that could be obtained from the technologies involved in the project are the following:

- **Cloud Point and photogrammetry** from the drones.
- **IoT data** from autonomous vehicles.
- **Environmental metrics** from IoT sensors installed in the different infrastructures and buildings.
- **IoT data from factory.**
- **Worker Conditions** from exoskeleton and wearable devices.
- **Geotechnical data** from maritime construction machine.

Acquisition Layer

The second layer refers to those software elements that allow the communication with the physical elements. This software will be responsible either for acquiring the information from the sensors or systems and for sending commands to them, providing a unified interface toward upper layers. Besides, the software after cleaning and preprocessing the data collected from the different systems, stores it in the databases. The middleware acts as a pivotal role between the data sources and the persistence layer to store only the meaningful data.

The communication between the different systems, devices, sensors, actuators and databases will be orchestrated by a middleware (see Figure 27) pushing different communication protocols. For this purpose, a browser-based flow editor called **NodeRED** will be used [view section 7]. This tool allows management and



data processing in real-time, managing and simplifying the processes between producers and consumers of information.



Figure 27. Digital Twin Data Acquisition Layer

Since the Data Source Layer is rather heterogeneous, as it includes many kinds of devices, the Data Acquisition Layer will have to implement several interfaces to establish successful communication with it. These interfaces should integrate the main data exchange mechanisms to allow the data intake from the different systems:

- **MQTT** is an Open Standard that implements a lightweight publish-subscribe protocol that transports messages between devices and systems. It usually runs over TCP/IP, although it can run also over other network protocols.
- **Application Programming Interface (API)**. An API uses web services to communicate using the HTTP protocol. A web service represents a standardized way of providing interoperability between disparate applications.
- **P2P or Peer-to-Peer** is a network where a group of machines participate in a completely decentralized way. There is not a central point of connection or control, where the parties act autonomously, responding to a common communication and consensus protocol. In this way the members of the network can exchange information directly and without intermediaries. In this project it will be the way that the autonomous vehicles exchange information with the drones.
- **LoRa** is technology used to create fully distributed and low power consumption networks (LPWAN). It is a protocol that can transmit small packages of information over long distances.
- **Sigfox** is a wireless communication network for the transmission of very small data over short distances. This technology is characterized by low transmission power, long range and low consumption.

This layer will be responsible for providing the different modules of the system with an abstract format that will facilitate interaction with the sensor network. This abstraction will be based on syntactic and semantic interoperability.

Data Persistence Layer

The Data Persistence Layer (see Figure 28) corresponds to the databases that store all the information necessary for the correct operation of the system. These databases will include:

- A relational data model for storing static information, such as configuration data, data relative to the buildings and infrastructure characteristics.



[D3.1: Digital Twin Design and Architecture]

- BIM models provided by the conception phases of the project or point clouds captured and processes by the UAV. It is a dynamic model that contains a whole series of information about geometry, materials, structures, characteristics among others.
- Dynamic data collected by the sensors (Monitoring database), which will be placed in a time-series database, more suitable for storing big amounts of information.
- BEEYONDERS architecture includes support to the utilization of both NoSQL databases and other SQL databases. These databases will be accessed and managed through a cloud provider, forming part of the business layer of the application.

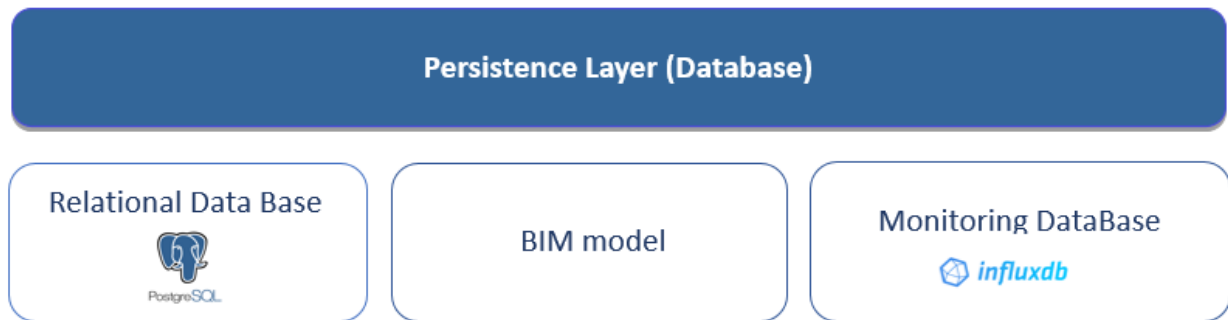


Figure 28. Digital Twin Persistence Layer

The data stored in the time-series database must have a direct relationship with the relational data model through a unique identifier, which is where the static information regarding the construction process and systems involved in is stored.

On the other hand, to store real-time data InfluxDB time-series database will be used. It is an open-source time series for fast, high-availability storage and retrieval of time series data in fields such as operations monitoring, application metrics, Internet of Things sensor data, and real-time analytics.

Business Layer

The business layer act as intermediate between the presentation layer and the persistence layer. This layer handles the business logic, business rules as well as calculations and analytics. It tells how the data from the database can be used, what it can perform, and what cannot within its application. Through the persistence layer, the business layer accesses the data collected by the acquisition layer and offers data processing, value addition and service transformation. The business layer is responsible for implementing the business logic of the Digital Twin, processing and manipulating data before it is presented to the user or stored in the database. It is also responsible for managing the workflows and the use cases of the application.

The management of the different buildings and infrastructures require accurate data in real time. Therefore, communication between the persistence layer and the business layer must work smoothly and uninterrupted. Once the data is accessible by the business layer, it must be processed to extract the information needed by the end user for decision making.

The tasks involved in this layer can be grouped in several common process which are represented in the next Figure 31.



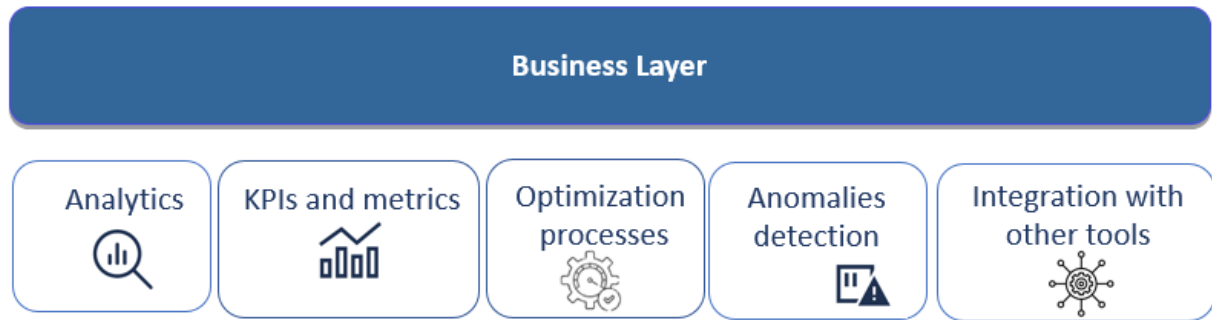


Figure 29. Business Layer tasks

In the scope of BEEYONDERS several applications based on AI for decision-making and improvement of wellbeing & safety of workers have been identified. These applications, materialized as input and output services, must be developed as independent services that cover each of the functionalities of the different use cases. Some examples of these services that will be implemented at the business layer are presented below:

Tunnel construction

- Perform off-line productivity analysis from cloud points comparison.
- Artificial Intelligence services to monitor the project progress, cost and maintenance needs.
- Perform KPIs related to the productivity and environmental metrics.
- Machine learning algorithms for anomaly detection or predictive maintenance.
- Provide alerts when certain thresholds are exceeded, or anomalies detected.

Road construction

- Photogrammetry comparison to obtain productivity.
- Off-line productivity analysis from cloud points comparison.
- Perform KPIs obtention and metrics of productivity, quality and safety.
- Environmental analyses to obtain related KPIs.
- Trajectory calculation to route optimization.
- Construction evolution analysis.
- Vegetation status identification from LIDAR.

Building construction

- Off-line productivity analysis and progress tracking from LIDAR comparison.
- Reflectivity analysis from LIDAR to detect surface and material textures.
- Task assignments to field workers based on the productivity and worker metrics.

Maritim construction

- Test and verify the biocompatibility of the coating before applying it to the structure
- Perform KPIs and metrics in terms of productivity and environmental impacts.



- Verify structural integrity and identify potential issues or weaknesses in the structure

Maritime construction (Japan)

- Geotechnical analysis.
- Predictions based on estimation of ground capacity and piling installation optimization.
- Economical and environmental KPIs from optimization results.
- Analysis of the success of the project and its impact on the environment.
- Provide real-time designs of governing pile lengths using installation resistance and geotechnical data.

Road maintenance

- Reflectivity analysis from painting marks on road and vegetation detected by the inspection vehicle and drones.
- KPIs obtention, in terms of resources optimised of avoiding human doing the inspection (for productivity, economy, workers, environmental...).
- Provide optimal routes for autonomous inspection vehicles based on real-time conditions and analysis of previous inspections.

Presentation Layer

The presentation layer is responsible of offering the user a friendly interface where the users can interact with the Digital Twin and the final data will be visible to them. It's the most visible layer and defines the application's overall look and presentation to the end-users. The main function of it is to translate task and results from the business layer into something that user can understand and use (Figure 30).

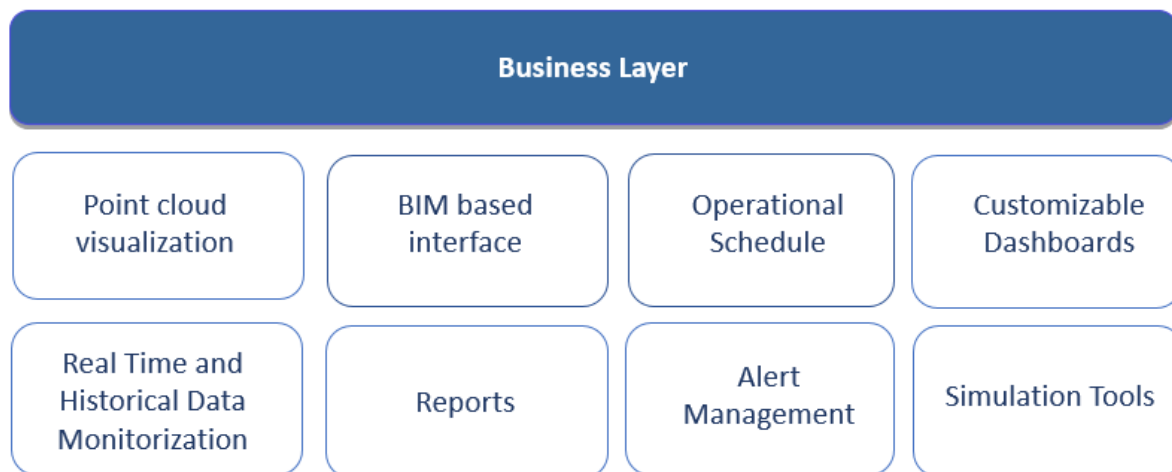


Figure 30. Presentation Layer tasks

Although each use case has its own particularities there are common modules that the presentation layer must support:



[D3.1: Digital Twin Design and Architecture]

- Point cloud visualization to track the progress of the different construction projects.
- BIM-based interface that enables users to interact with the digital twin and gain insights into the project's progress, performance, and behavior.
- Operation schedule that provides information about the tasks that must be executed on a specific day.
- Real-time and historical data monitorization about the building or infrastructures that allows to monitor the progress and identify deviations.
- Customizable dashboards that provide a visual interface for KPIs and metrics of productivity, quality, and safety.
- Report generation to evaluate the project progress, costs and risk based on historical data.
- Simulation tool that allows calculate optimal routes and make predictions about future outcomes or behaviors.

These interfaces are more detailed in section 9 of this deliverable.

Communication Across Layers

The communication between layers is typically achieved through APIs (Application Programming Interfaces) that allow different components to interact with each other. For example, the presentation layer may send requests to the load balancer to distribute incoming traffic across multiple virtual machines. The virtual machines will then communicate with databases to store or retrieve data. In addition to APIs, there are other mechanisms for communication across layers in this architecture. For example, security services may be used to ensure that only authorized users or systems can access certain components of the system. This may involve authentication and authorization mechanisms such as OAuth2 or OpenID Connect.

Due to the nature of BEEYONDERS project, big data is an important aspect of this cloud architecture, as it involves the processing and analysis of large volumes of data generated by the 6 Business Cases involving various sources of information relying on the Breakthrough Technologies (BT). In this regard, an important aspect of communication across layers is data integration and processing. In this architecture, we propose a data lake and a data analytics platform supporting historical data analysis and machine learning scenarios. These components are responsible for processing large volumes of data generated by various sources in the system.

The datalake is a central repository for storing large volumes of structured and unstructured data. It provides a scalable and cost-effective solution for storing data that can be accessed by different components in the system. The datalake can be used to store data from various sources such as IoT devices, sensors, or other systems. On the other hand, the analytics platform supports big data processing and machine learning through the use of parallel computing techniques as it provides a scalable and distributed computing environment that can process large volumes of data in parallel. The platform can be used to perform various tasks such as data cleaning, transformation, analysis, and modeling before performing analysis or machine learning modeling.

In addition to communication between components, there are other aspects of big data processing that are to be considered in this architecture. For example, security services may need to be implemented to ensure that sensitive or confidential information is protected from unauthorized access or disclosure.



Platform Software Environment

Technology Choices for the common platform (general Architecture)

BEEYONDERS system will be designed as a hybrid cloud-based and on-premise architecture, with different components working together to support the common workflow. The architecture will be designed to be scalable, reliable, and secure. The basic elements of the cloud architecture will include:

- **Cloud Service Provider:** The cloud service provider will provide the infrastructure and services needed to host the system in the cloud. This may include services such as virtual machines, storage, networking, and security.
- **Virtual Machines:** Virtual machines will be used to host the different components of the system, such as InfluxDB, Node-RED, PostgreSQL, etc. Each virtual machine will be configured with the necessary resources (such as CPU, memory, and storage) to support its specific workload
- **Load Balancer:** A load balancer will be used to distribute incoming traffic across multiple virtual machines. This helps to ensure that the system can handle large amounts of traffic without becoming overloaded. There are several load balancing tools that can be used to distribute traffic across multiple virtual machines in a cloud environment. The specific tool to be chosen will depend on the cloud service provider being used. Here are some popular options:
 - a. Amazon Elastic Load Balancer (ELB): This is a fully managed load balancing service provided by Amazon Web Services (AWS). It automatically distributes incoming traffic across multiple EC2 instances and can scale up or down based on demand.
 - b. NGINX: This is a popular open-source web server that can also be used as a load balancer. It supports HTTP, HTTPS, TCP, and UDP protocols and can be configured to distribute traffic based on various criteria such as round-robin, IP hash, or least connections.
 - c. HAProxy: This is another open-source load balancer that supports HTTP, HTTPS, TCP, and UDP protocols. It can be configured to distribute traffic based on various criteria such as round-robin, least connections, or source IP address
 - d. Microsoft Azure Load Balancer: This is a load balancing service provided by Microsoft Azure. It can distribute incoming traffic across multiple virtual machines in the same availability set or across availability zones.
 - e. Google Cloud Load Balancing: This is a load balancing service provided by Google Cloud Platform (GCP). It can distribute incoming traffic across multiple virtual machines in the same region or across regions.
- **Databases:** InfluxDB will be used as a time-series database for storing real-time data from sensors and other devices, while PostgreSQL will be used to store relational data, such as BIM Models. Azure Data Lake System will be used for storing structured and unstructured data that is processed by Databricks.
 - a. Azure Data Lake Storage is an scalable data lake that can store petabytes of data in its native format. It provides a hierarchical file system that can be accessed using standard Hadoop Distributed File System (HDFS) APIs or REST APIs. Azure Data Lake Storage supports multiple file formats including CSV, JSON, Parquet and ORC.



[D3.1: Digital Twin Design and Architecture]

- b. InfluxDB can be used to collect and store time-series data, which can then be ingested into Azure Data Lake Storage for further analysis. Azure Data Lake Storage provides a scalable and cost-effective solution for storing large amounts of data over long periods of time. Time-series data stored in InfluxDB can be periodically archived to Azure Data Lake Storage for long-term retention
 - c. BEEYONDERS architecture will support the utilization of NoSQL databases offering flexibility and scalability, and enabling efficient handling of unstructured or rapidly changing data. These databases will be accessed and managed through a cloud provider, forming part of the business layer of the application.
- **Middleware:** The middleware layer is responsible for integrating data from different sources into the cloud data service. It acts as a bridge between the devices and sensors that collect data and the cloud-based analytics platform that processes and analyzes that data. The middleware layer is also responsible for ensuring that the data is in a format that can be easily consumed by the analytics platform. Node-RED will be used as a middleware tool to support as the responsible for integrating data from different sources into the system. Node-RED has several capabilities that make it well-suited for use as a middleware layer:
 - a. Integration with multiple protocols: Node-RED supports RESTful and MQTT protocols (as well as Sigfox and LoRa), which are commonly used in IoT applications. This makes it easy to integrate data from different devices and sensors into the cloud data service.
 - b. Easy-to-use visual interface: Node-RED's drag-and-drop interface makes it easy to create complex flows without writing any code. This reduces development time and makes it easier to maintain the system over time.
 - c. Large library of pre-built nodes: Node-RED has a large library of pre-built nodes that can be used to integrate with popular services such as Twitter, Slack, and AWS. This reduces development time and makes it easier to add new functionality to the system.
 - d. Scalability: Node-RED can be deployed on multiple virtual machines to support high levels of traffic or large amounts of data.

The proposed middleware components and the interrelation as a system are shown in the diagrams below (see Figure 31 and Figure 32).

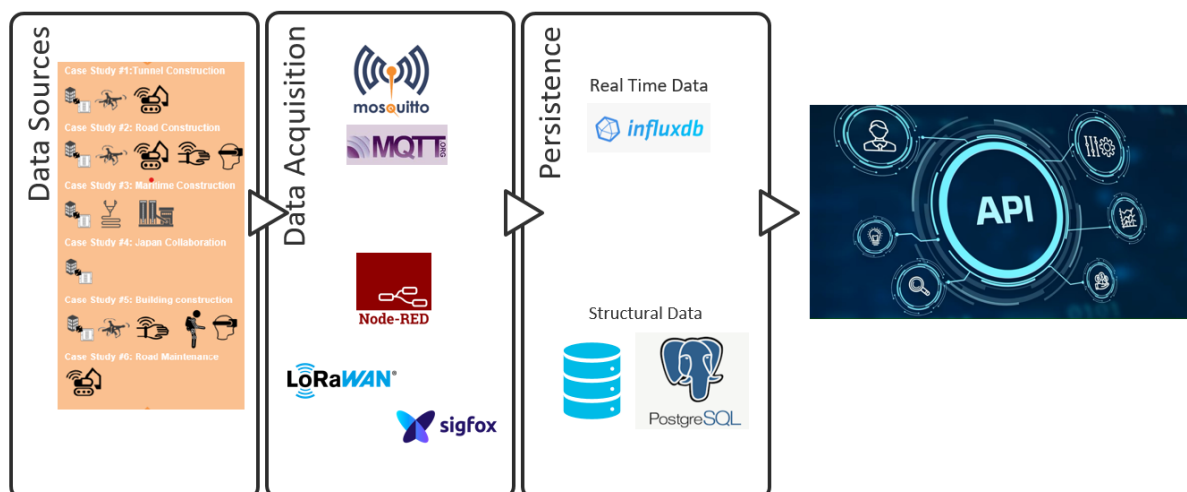


Figure 31. Middleware Components



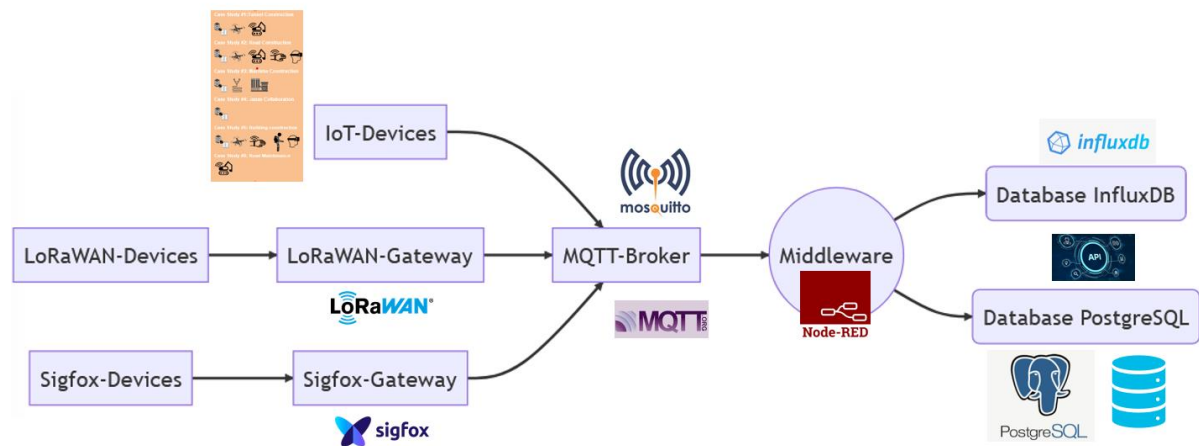


Figure 32. Middleware Component Communication

- **Analytics Platform:** The analytics platform is responsible for processing and analyzing the data collected from the devices and sensors in the cloud-based architecture. It provides tools for data scientists and developers to extract insights from the data, build predictive models, and generate reports. Databricks will be used for processing large amounts of data in parallel using Apache Spark. Databricks is a distributed computing framework that can be used as an analytics platform in cloud-based architectures. It provides a unified analytics engine for big data processing that supports batch processing, stream processing, machine learning, and graph processing. Databricks Spark has several capabilities that make it well-suited for use as an analytics platform:
 - a. Distributed computing: Databricks can distribute computations across multiple nodes in a cluster, which allows it to process large amounts of data quickly.
 - b. In-memory processing: Databricks Spark stores data in memory, which allows it to access and process data much faster than traditional disk-based systems.
 - c. Support for multiple languages: Databricks Spark supports multiple programming languages including Python, R, SQL, Java, and Scala. This makes it easy for developers to work with the platform using their preferred language.
 - d. Machine learning libraries: Databricks Spark includes several machine learning libraries such as MLlib and TensorFlow that can be used to build predictive models.
 - e. Graph processing: Databricks Spark includes a graph processing library called GraphX that can be used to analyze large-scale graphs such as social networks or transportation networks.
- **User Interface Layer:** The user interface layer will provide a web-based interface for users to interact with the system. It may include features such as customizable dashboards, real-time updates, and alerts. It is responsible for presenting data and information in a way that is easy to understand and use. In the context of a BIM-based cloud platform, the user interface layer will have several capabilities:
 - a. BIM and cloud points visualization: The user interface layer will provide capabilities to visualize BIM models and cloud points in 3D. This will allow users to see the current physical reality of the construction site and monitor progress over time.
 - b. Dashboard: The user interface layer will include a dashboard that provides an overview of key performance indicators (KPIs), metrics, and other data points related to the construction



[D3.1: Digital Twin Design and Architecture]

- project. The dashboard can be customized to show only the information that is relevant to each user.
- c. Real-time data visualization: The user interface layer will provide capabilities to visualize real-time data from sensors, IoT devices, and other sources. This can include visualizations such as charts, graphs, or maps that update in real-time as new data becomes available.
 - d. Historical data visualization: The user interface layer will also provide capabilities to visualize historical data from sensors, IoT devices, and other sources. This can include visualizations such as trend lines that show how data has changed over time.
 - e. User customization: The user interface layer can be customized by individual users based on their preferences or needs. For example, users may be able to choose which KPIs or metrics are displayed on their dashboard or customize the layout of their 3D visualization.
- **Security:** Security measures such as firewalls, encryption, access control mechanisms, and monitoring tools will be implemented to protect the system from unauthorized access or attacks.
 - a. Firewalls: Firewalls are used to monitor and control incoming and outgoing network traffic based on predefined security rules. They can be configured to block traffic from known malicious IP addresses or to allow traffic only from trusted sources.
 - b. Encryption: Encryption is used to protect data in transit and at rest by converting it into a form that can only be read by authorized parties. This prevents unauthorized access to sensitive data even if it is intercepted during transmission or stolen from storage.
 - c. Access control mechanisms: Access control mechanisms are used to ensure that only authorized users have access to the cloud-based architecture. This can include user authentication using passwords or multi-factor authentication, role-based access control (RBAC), or attribute-based access control (ABAC).
 - d. Monitoring tools: Monitoring tools are used to detect and respond to security incidents in real-time. They can be configured to alert administrators when suspicious activity is detected or when predefined security thresholds are exceeded.

There are several cloud tools that can be used to implement the security platform in a cloud-based architecture. Here are some popular options:

- a. Amazon Web Services (AWS) Security Hub: This is a security service provided by AWS that provides a comprehensive view of security alerts and compliance status across multiple AWS accounts. It integrates with other AWS services such as Amazon GuardDuty, AWS Config, and AWS Identity and Access Management (IAM) to provide a centralized location for managing security.
- b. Microsoft Azure Security Center: This is a unified infrastructure security management system provided by Microsoft Azure. It provides threat protection across hybrid workloads, detects and responds to attacks, and provides advanced analytics to help identify potential threats.
- c. Google Cloud Security Command Center: This is a security management system provided by Google Cloud Platform (GCP). It provides centralized visibility into assets, vulnerabilities, and threats across GCP services and third-party data sources.
- d. HashiCorp Vault: This is an open-source tool for managing secrets such as passwords, API keys, and certificates. It can be used to securely store sensitive information in the cloud-based architecture.
- e. Cloudflare: This is a cloud-based web application firewall (WAF) that protects websites from attacks such as SQL injection and cross-site scripting (XSS). It can be used to protect web applications running in the cloud-based architecture.



[D3.1: Digital Twin Design and Architecture]

Sensor platform: In the cloud-based architecture, a sensor platform or data acquisition platform is responsible for collecting and integrating real-time data from various sources such as drones, wearables, IoT sensors, and autonomous vehicles. These data sources are used to monitor the construction site and provide insights into the progress of the project. The sensor platform will be designed to handle large amounts of data from multiple sources in real-time. It will use a scalable microservices architecture that can be deployed on top of the cloud infrastructure. The microservices will be responsible for collecting data from each source and integrating it into a common format that can be used by other components in the architecture. The integrated data can then be used by other components in the architecture such as Azure Data Lake Storage or Azure Data Lake Analytics for further analysis and visualization.

- a. The drones will be equipped with LIDAR scanners that can collect point cloud data of the construction site. This data can be used to create 3D models of the site that can be visualized in real-time using the user interface layer.
- b. The wearables will be equipped with an IoT system that can collect data on temperature, humidity, VOC, particle measurement, CO₂, man-down events, GPS location, and other parameters related to worker safety and health.
- c. The IoT sensors will be deployed throughout the construction site to collect data on environmental conditions such as temperature, humidity, air quality, noise levels, and vibration.
- d. Autonomous vehicles such as trucks or cranes may also have sensors that collect data on their performance or location. All of this real-time data will be integrated into a common format using the microservices architecture.

The basic architecture of the system and the interrelation of components can be observed in the following architecture diagram (see Figure 33).



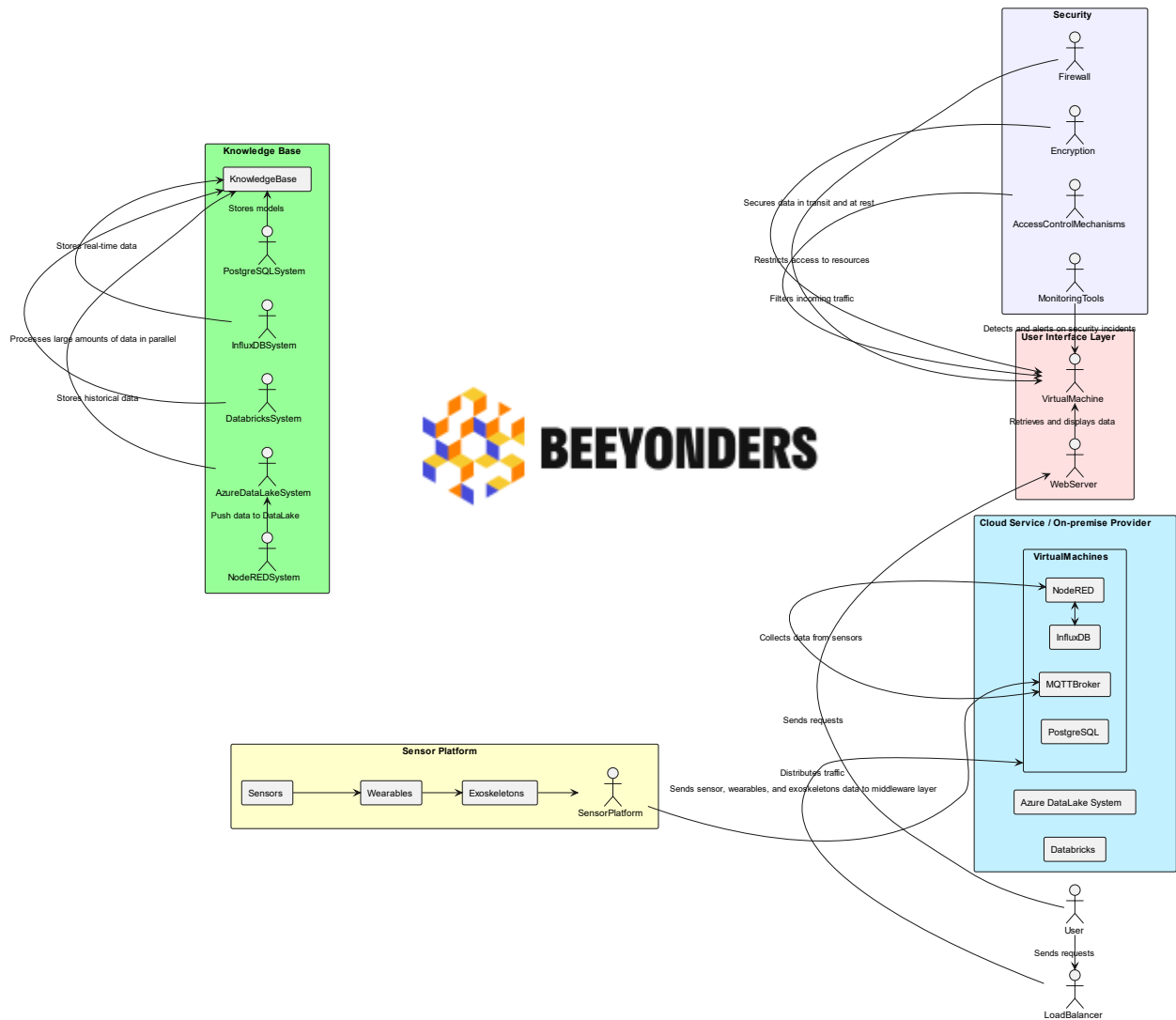


Figure 33. BEEYONDERS Hybrid Architecture

Technical requirements for the Breakthrough Technologies in the Sensor Platform

The deliverable D2.2 provides technical requirements for several technologies related to construction processes. Below is a summary of the communication requirements for each of the project Breakthrough Technologies (BT). The requirements that should be taken into account for the integration of the BT in the BEEYONDERS system are described below. In bold faces, there are some considerations regarding the communication protocols that these sensor platforms should comply with.



Autonomous / Semi operated Wheel Loader

The technology aims to transform a wheel loader machine into an autonomous vehicle capable of performing advanced driving tasks in short or large cycles and specific earth-moving tasks. The technical requirements for this BT is described in Table 23.

Requirement No.	Requirement Description
BTR1.1	A complete set of software modules like path planning, objects avoidance, etc will be developed and the system proposed on T4.2 and T4.3 will be used in combination with the other robots/machines developed in T4.4 and T4.5.
BTR1.2	LiDAR's and cameras will be integrated on the machine, generating the data to detect objects and localising other machines on the environment.
BTR1.3	A hierarchical task and motion planning algorithms that combine learning-based techniques (reinforcement learning control) with optimization-based methods will be integrated in parallel to the perception module, considering the multiple parameters that can affect on the loading and dumping process.
BTR1.4	A combination of multi domain rewards in the learning process will be used while the machine is controlled tele-operated or autonomously.
BTR1.5	Sensors will be commercial: LIDAR, Radar, Pressure sensors, temperature sensors, cameras, 360 degrees visual systems, integrated potentiometers, electronically controlled brake systems (brake by wire), electronically controlled steering systems (steer by wire), electronic control units, angle sensors, proximity sensors, accelerometers, electronic joysticks, and operator seat station.
BTR1.6	The AWL will have the specifications as follows: 210 kW engine power, 20600 kg operation weight, 40 kph max. speed, 3,5 m3 bucket capacity, 5 speed transmission.
BTR1.7	Degree of autonomous operation: AWL will be Level 4.
BTR1.8	Variables to be monitored and sent to the DT database: machine engine Revolutions per minute, machine speed, pressure and flow values, mechanism positions, dynamic behavior of the machine, hydraulic cylinders' positions, machine location, pile amount and location, interrelation with surroundings (human around the machine, obstacles).
BTR1.9	Communication protocols: CANBUS SAE J1939. The CANBUS system should integrate a gateway that transforms the data into any compatible protocol available in the Middleware (MQTT, LoRa, Sigfox, RESTful)
BTR1.10	AWL and human around the machine should interact.

Table 23. Autonomous / Semi operated Wheel Loader Requirements



Autonomous Aerial Vehicles

The technology aims to develop autonomous aerial vehicles for inspection and monitoring purposes in construction sites. The technical requirements for this BT is described in Table 24.

Requirement No.	Requirement Description
BTR1.1	The UAV must be able to scan the tunnel autonomously
BTR1.2	The UAV must be able to generate a map of the environment with the current state of the tunnel
BTR1.3	The UAV must be able to fly and localize itself inside the tunnel
BTR1.4	The UAV must be able to detect obstacles closer than X meters
BTR1.5	The UAV must take off and land autonomously, always with a safety pilot supervision
BTR1.6	Sensors will be commercial: RGB camera, 3D LIDAR, IMU.
BTR1.7	Specifications: there will be different platforms: aerial robots for outdoor use cases will be LARGER than 1.5m diagonal base.
BTR1.8	The UAV must be able to exchange information X directly with the autonomous wheel loader without mediation of the Digital Twin
BTR1.9	The UAV must be able to send information X to the DT system. The information includes 3D Maps that could be uploaded to the Datalake through an API or GUI
BTR1.10	Communication protocols: ROS as middleware (Robot Operating System) and Standard IP-based protocols.

Table 24. Autonomous Aerial Vehicles Requirements

Autonomous Ground Mobile Inspection Vehicle

The technology aims to develop autonomous ground mobile inspection vehicles for inspection and monitoring purposes in construction sites. The technical requirements for this BT is described in Table 25.

Requirement No.	Requirement Description
BTR1.1	It is required a vehicle for road (no off-road capability expected) and outdoor use. It should be capable of traveling several kilometres long road stretches in a reasonable time and without the need for recharging.
BTR1.2	The vehicle should be operable in both sunny and light rain conditions, though operation in bad weather conditions could be limited by sensors' capabilities.
BTR1.3	Manoeuvrability is not a priority, so Ackerman or double Ackerman steering should be preferred for higher speeds.
BTR1.4	It should have enough payload to easily accommodate a variety of equipment and sensors required.
BTR1.5	Size should be medium-small to easy logistics and transportation.
BTR1.6	Size: 1100×700×450mm; Weight: 200Kg; Payload 120Kg; Speed: 15 Km/h; Autonomy: 65 Km.
BTR1.7	Sensors: 3D/2D LiDAR, 2D cameras, GPS, IMU, RADAR, ultrasonic, retro reflectometer. All commercial devices integrated in the platform.
BTR1.8	Retroreflectometer sensor requires to be adapted to the vehicle and able to



	provide an API connection to extract the data. Identified sensor is EasyLux Retroreflectometer MiniReflecto Horizontal 30-meteri
BTR1.9	Variables to be monitored and sent to the DT database: telemetry from the vehicle, road measurements, GPS position. The Autonomous Ground Mobile Inspection Vehicle should integrate a gateway that transforms the data into any compatible protocol available in the Middleware (MQTT, LoRa, Sigfox, RESTful)
BTR1.10	Communication networks / protocols: Wi-Fi, 4G / ROS based TCP communications through Wi-Fi.

Table 25. Autonomous Ground Mobile Inspection Vehicle Requirements

Optimized and Bio Compatible Mortars

The technology aims to develop optimized and bio-compatible mortars for use in construction processes. The technical requirements for this BT is described in Table 26.

Requirement No.	Requirement Description
BTR1.1	Variables that are going to be measured after manufactured (Structural behaviour, hardness, biolife implementation): Moisture of aggregates, temperature of concrete or mortar raw materials, wattmeter curves in the concrete mixer, colonization of these surfaces over time (and possibly cracking monitoring), ideally complexity, rugosity and pH, structural health of the caisson (accelerometers, potentiometers, etc.)
BTR1.2	Communication protocols that are planned to be employed during IoT deployment of manufacturing: MQTT. The system should integrate a gateway that transforms the data into any compatible protocol available in the Middleware (MQTT, LoRa, Sigfox, RESTful)

Table 26. Optimized and Bio Compatible Mortars Requirements

Exoskeleton

The technology aims to develop exoskeletons for use in construction processes to assist workers in lifting heavy loads and reducing the risk of injury. Additionally, the exoskeleton must be comfortable to wear for extended periods of time and be adjustable to fit different body types. The technical requirements for this BT is described in Table 27.

Requirement No.	Requirement Description
BTR1.1	Variables that are going to be measured in experimental campaigns are: • Force and torque: Exoskeletons can measure the forces and torques applied by the user during construction tasks, such as lifting and moving heavy objects or using power tools. • Muscle activity: Exoskeletons can measure the electrical signals produced by the user's muscles, which can provide information about muscle activation and fatigue. • Joint angles and range of motion: Exoskeletons can measure the angles of the user's joints and the range of motion during construction tasks, which



	can help to identify ergonomic risks and design interventions to reduce injury risk. • Posture and balance: Exoskeletons can measure the user's posture and balance during construction tasks, which can help to identify ergonomic risks and design interventions to reduce injury risk. • Heart rate and other physiological measures: Some exoskeletons are equipped with sensors that can measure the user's heart rate, respiration rate, and other physiological measures, which can provide information about the user's physical exertion and stress levels.
BTR1.2	The exoskeleton shall have the functionality of sending and share data and technical information to the wearable systems. No direct connection to the Digital Twin Platform is foreseen. The interfacing with the Digital Twin will be carried out by the Wearables Systems, which will integrate the data coming from the exoskeletons. Exoskeletons send live data to the Digital Twin. This data includes the worker's location, activity, and sensor information. Additionally, offline processing is conducted to obtain more complex analyses, such as fatigue studies and ergonomics. These studies are conducted by IIT locally and only the results are sent to the Digital Twin. The Exoskeletons and the local interfaces should integrate a gateway that transforms the data into any compatible protocol available in the Middleware (MQTT, LoRa, Sigfox, RESTful)

Table 27. Exoskeleton Requirements

Smart Wearables

The technology aims to develop smart wearables for use in construction processes to monitor worker health and safety. The technical requirements for this BT is described in Table 28.

Requirement No.	Requirement Description
BTR1.1	Sensors: IMU (Inertial Measurement Unit: acceleration and gyration) and, for ground truth data (not to be used in digital twin), EMG (electromyogram) and EKG (electrocardiogram) are considered at the moment.
	Variables to be monitored and sent to the DT database: • Aggregated activity recognition data from IMU (accelerometer, gyroscope, magnetometer), and other aggregated physiological parameters, if allowed by GDPR. • Aggregated activity recognition and performance from wearables systems • Location and routes tracking of workers.
BTR1.2	A SIM module / mobile edge device can be used to send data collected from the sensors to the cloud platform. Depending on the case study and requirements of the Digital Twin, technologies such as Bluetooth and Wi-Fi can be adopted to exchange data.
BTR1.3	Communication protocols: Bluetooth, TCP/IP, MQTT. The sensors monitor the worker and calculate aggregated data with edge devices. The edge devices should



	integrate a gateway that transforms the data into any compatible protocol available in the Middleware (MQTT, LoRa, Sigfox, RESTful)

Table 28. Smart Wearables Requirements

Next steps in the development of WP3 platform

Implementing this architecture will involve several steps. Here are the high-level steps that developers should carry out:

1. Choose a cloud service provider: The first step is to choose a cloud service provider that meets the project's requirements for scalability, reliability, and security. Some popular options include Amazon Web Services (AWS), Microsoft Azure, and Google Cloud Platform.
2. Set up virtual machines: Once the cloud service provider has been chosen, developers will need to set up virtual machines to host the different components of the system. Each virtual machine should be configured with the necessary resources (such as CPU, memory, and storage) to support its specific workload.
3. Install and configure software components: Next, developers will need to install and configure the software components of the system on each virtual machine. This may include InfluxDB, Node-RED and the MQTT Broker. Cloud provider resources need to be allocated, such as Azure Data Lake System, Databricks, and other tools as needed.
4. Set up load balancing: To ensure that the system can handle large amounts of traffic without becoming overloaded, developers will need to set up load balancing. This involves configuring a load balancer to distribute incoming traffic across multiple virtual machines.
5. Set up databases: Developers will need to set up databases for storing real-time data from sensors and other devices (using InfluxDB) as well as processed data (using Azure Data Lake System).
6. Configure middleware layer: Node-RED will be used as a middleware layer to support RESTful and MQTT protocols (as well as Sigfox and LoRa). Developers should configure Node-RED to integrate data from different sources into the system.
7. Configure analytics platform: Databricks will be used for processing large amounts of data in parallel using Apache Spark. Developers should allocate and configure a Databricks instance with the necessary resources (such as CPU cores and memory) to support its workload.
8. Set up user interface layer: The user interface layer will provide a web-based interface for users to interact with the system. Developers should set up a web server and configure it to retrieve and display data from the virtual machines.
9. Implement security measures: Finally, developers will need to implement security measures such as firewalls, encryption, access control mechanisms, and monitoring tools to protect the system from unauthorized access or attacks. These are the high-level steps that developers should carry out to implement this architecture. The specific details of each step will depend on the project's



[D3.1: Digital Twin Design and Architecture]

requirements and the cloud service provider chosen. It is recommended that developers consult with a cloud architect or other expert to ensure that their implementation is secure and scalable



Visualization Interfaces

BEEYONDERS is studying various use cases with different objectives, different stakeholders and different knowledge to be presented to the end-users.

In that context the visualization interfaces we must be iteratively adapted to the requirements of the different use cases, but for consistency purposes, BEEYONDERS user interfaces have to follow overall guidelines. This section describes the overall approach regarding visualization interfaces that will support BEEYONDERS services.

The following schema presents the proposed categorization breakdown for the visualisation of key performance indicators (KPIs), properties and measures which will be produced by the BEEYONDERS project:

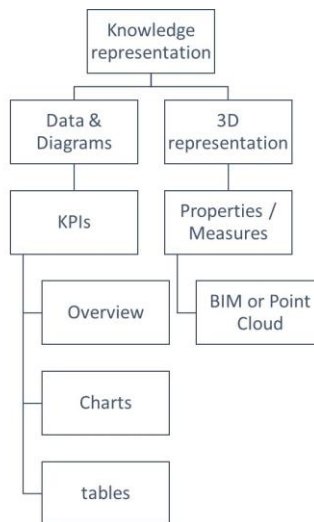


Figure 34 categorization breakdown for the visualisation PKIs

The BEEYONDERS knowledge representation will be presented in 2 main visualisation categories which are the “data and diagrams representation” and the “3D representation”.

The “**data and diagrams representation**” will expose the different calculated KPIs presenting them in:

- an **Overview** section holding the most important KPIs for stakeholders to take a decisions
- the **Charts** section where KPIs are presented as charts (ex: column Chart ,Bar Chart ,Line Chart ,Area Chart ,Pie Chart ,Scatter Plot ,Bubble Chart ,Gauge etc.)
- and the **Table** section where data can be displayed in tables and may be exported as CSV files if required.

A KPI is a measurable and quantifiable metric used to track BEEYONDERS progress towards a specific goal or objective. KPIs will gauge BEEYONDERS outputs against a set of targets and objectives.

The “**3D representation**” will hold properties or measures of real-world data presented in a 3D **IFC numeric model** or a **point cloud** display. Properties are high level indicators representing business information about



the site (e.g is the place safe or not?) whereas measurements are machines, sensors or devices collected the data.

Depending on requirements, KPIs, properties or measures retrieval from the DT may be adjustable based on queries using dates ranges inputs or other relevant discriminant parameters. These specific restrictions of the KPIs rendering will be defined iteratively during the project.

The choice is made to propose visualisation interfaces **through a web interface** to have them more available to the difference BEEYONDERS users without having to install specific applications other than a state-of-the-art web browser.

Here is the consistent logic of the BEEYONDERS KPI interfaces:

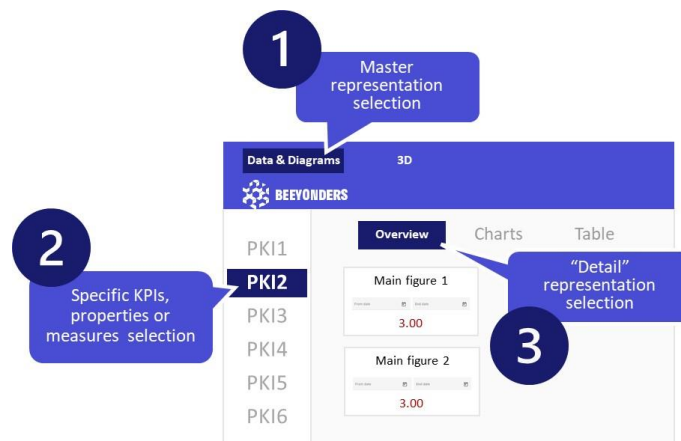


Figure 35 logic of the BEEYONDERS KPI interfaces



The next figure presents sample wireframes of the possible BEEYONDERS interfaces’ layouts:

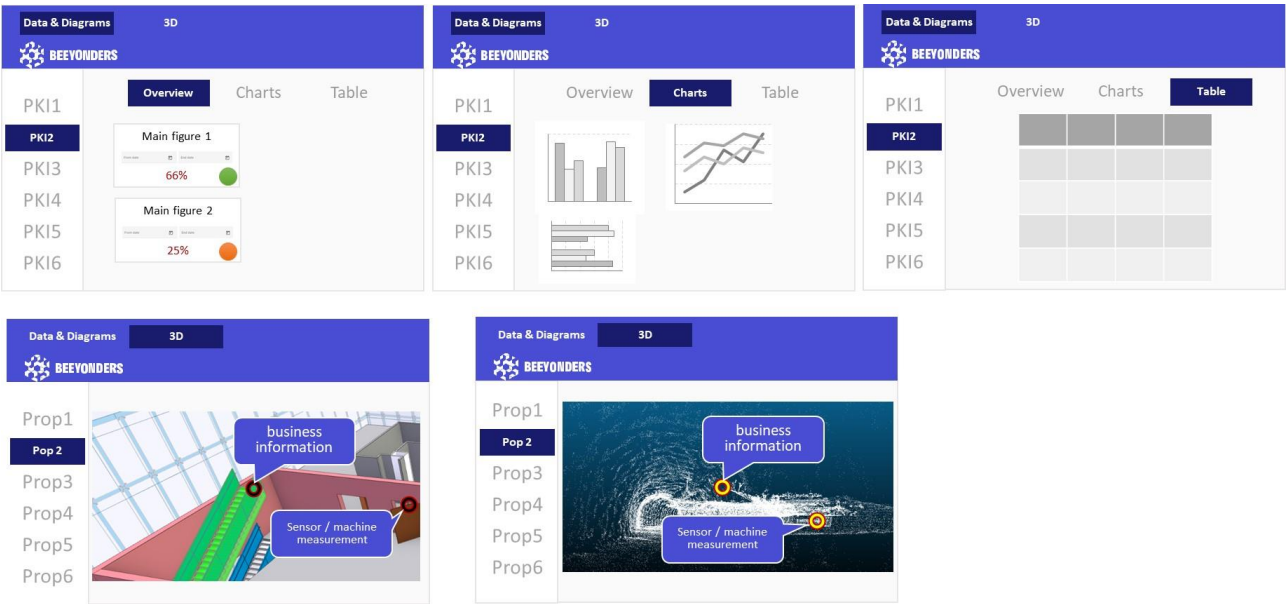


Figure 36 BEEYONDERS KPI interfaces wireframes



Conclusions

BEEYONDERS is a project that aims to address the main challenges in the construction industry by developing and integrating Breakthrough Technologies (BT) from other industrial sectors. The project's goal is to achieve technological sovereignty in construction, which means that the European construction industry will be able to develop and use its own technologies without relying on imports from other countries.

The project's requirements and results can be defined as a system with inputs and outputs. The inputs are the challenges that the construction industry faces, such as labor shortages, an aging workforce, and a lack of innovation. The outputs are the results that the project aims to achieve, such as improved efficiency, safety, and quality in construction, as well as reduced environmental impact.

The project's consortium is made up of a group of organizations from the construction industry, academia, and the public sector, which have developed a methodology for the project that will allow it to begin with technologies at a certain level of maturity (TRL4) and reach a higher level of maturity (TRL6) by the end of the project. The project will use an iterative process to develop the technologies, moving from concept and design to lab testing and then to use-case demonstrations. BEEYONDERS has 10 general objectives with sub-objectives that are to be achieved at the end of the project and has also defined several potential key performance indicators (KPIs) and key results (KERs) that will be used to measure the project's success.

In this context, the Deliverable 3.1 "Digital Twin Design and Architecture" corresponds to the completion of Task 3.1, with the same name as this deliverable, of WP3 "Digital Twin and Diagnostics". This deliverable aims to provide a detailed description of the design and architecture of the BEEYONDERS platform, which is a digital twin in the construction sector. The platform is expected to increase productivity while improving quality, cost efficiency, and project delivery. The document includes several sections that describe different aspects of the platform's design and architecture, such as technical requirements, modular architecture definition, platform software environment and visualization interfaces. These sections provide information about the functional and non-functional requirements of the system, its different layers at the IT level and their communication, technology options selected for the platform's development leading to an operational validation and visualization tools used in the platform, among other aspects.

The section 3 "Users and expectations of the platform" provides information about the different user roles and their expectations from the BEEYONDERS platform. In this regard, it explains that there are three main user roles: construction companies, technology providers, and end-users. Construction companies are expected to use the platform to manage their projects, while technology providers will use it to offer their services and products. End-users will benefit from the platform by having access to innovative solutions that improve their productivity and quality of life. The section also highlights some of the expectations from the platform, such as providing a collaborative environment for all stakeholders, offering real-time data analytics, and ensuring data privacy and security.

In section 4 "Workflows for the use cases" we provide information about the operational scheme and workflows for each use case in the BEEYONDERS project. The section explains that each use case will have a BPMB diagram and key points to follow, which will converge in a general workflow (Common Workflow) that defines the core of the platform architecture. The section also lists the type of KPI produced as output in each use case, which is one of the key outputs of the Digital Twin. Finally, it highlights that the Digital Twin and KPIs function as a visual repository of data generated by different breakthrough technologies applied in the various use cases.



[D3.1: Digital Twin Design and Architecture]

The section 5 "Technical Requirements" provides information about the functional and non-functional requirements of the BEEYONDERS platform. The section explains that functional requirements are the main technical characteristics of the system that meet the requirements or tasks expected by end-users, while non-functional requirements solve intermediate technical needs to achieve such functionalities. The section also includes tables indicating these requirements.

The section 6 "Modular Architecture Definition" provides conceptual information about the different levels of the BEEYONDERS platform at the IT level and their communication schema. The section explains that there are three main layers: Data, Acquisition, and Business Layers. The Data Layer is responsible for storing and managing data, while the Acquisition Layer is responsible for collecting data from various sources. The Business Layer is responsible for processing data and providing insights to end-users. The section also includes graphical diagrams showing the conceptual design of the Digital Twin and data platform to illustrate how these layers communicate with each other. Additionally, the section details the different levels (Data, Acquisition and Business Layers) of the system at the IT level, as well as the communication between them. For this purpose, graphical diagrams showing the conceptual design of the Digital Twin and data platform are presented.

The section 7 "Platform Software Environment" provides information about the technology options selected for the BEEYONDERS platform and the steps to be followed in its development leading to an operational validation. The section describes the selected technology options that are justified in detail, prior to IT implementation and use case testing. Finally, the section summarizes the key aspects of the proposed design of the Digital Twin and data platform, as well as what is expected in relation to the next tasks, including the development and practical implementation of the design.

Finally, the section "Visualization Interfaces" provides information about the visualization tools used in the BEEYONDERS platform, such as BIM viewers and raw Cloud Point viewers. The section explains that the visualization tools include proprietary, existing free tools to be incorporated in the process, and other standard tools in certain sub-processes that might be considered necessary.

Summarizing, the Deliverable D3.1 captures the essential elements of the BEEYONDERS digital twin architecture design, which will be implemented for the 6 project Use Cases. It explores the different components of the architecture, the associated challenges, and the recommended practices for ensuring successful implementation. The architecture design encompasses the necessary hardware, software, data, and networking components for constructing, operating, and maintaining the digital twin. Considerations such as scalability, interoperability, security, and data privacy, as non-functional requirements, will be considered in the design process. The proposed architecture has been delivered by understanding the specific requirements and execution of the use cases, incorporating information from D2.2 - Technical Requirements and workshops conducted during this phase in WP2 to enhance the use case details. Workflows for each use case are presented to identify the required data exchange with the digital twin during use case execution and to highlight the critical steps where the digital twin plays a crucial role. The proposed architecture follows a modular and flexible approach, allowing for the integration of diverse data sources from BEEYONDERS technologies and adaptability to future changes.



APPENDIX

This appendix contains several UML diagrams that support the use cases that will be developed in this project. The diagrams are presented in PlantUML format, which is a plain text language for creating UML diagrams. The diagrams in this appendix are intended to provide a visual representation of the system and its interactions. They can be used to help understand the system, identify potential problems, and communicate the system design to others.

The diagrams are organized by use case. Each use case diagram shows the actors that interact with the system, the system's functionality, and the flow of events for each use case. The diagrams are also accompanied by brief descriptions that provide additional information about the system and its features.

Online viewers can be found here:

<https://www.gituml.com/plantuml#>

<https://plantuml-editor.kkeisuke.com/>

Just copy and paste the use cases diagrams to edit its content.

Use Case 1: Tunnel Construction

This use case describes how the BEEYONDERS system can be used to improve the efficiency and safety of tunnel construction. The system uses a combination of sensors, drones, and machinery vehicles to collect data about the tunnel construction site in real time. This data is then used to create a digital twin of the tunnel, which can be used to plan and execute construction activities more effectively. The system can also be used to monitor the progress of construction and identify potential problems early on.

@startuml

actor User

participant "Digital Twin Platform" as DT

participant "Sensor and Drone Network" as SDN

participant "Machinery Vehicles" as MV

User -> DT: Access Digital Twin interface

User -> DT: Check scheduled program for tunnel construction

activate DT

DT -> SDN: Collect real-time data from sensors and drones

SDN -> DT: Send real-time data to Digital Twin platform

DT -> MV: Send instructions to machinery vehicles

MV -> DT: Send status updates to Digital Twin platform

deactivate DT

User <- MV: Receive progress updates from machinery vehicles



@enduml

Use Case 2: Road Construction

This use case describes how the BEEYONDERS system can be used to improve the efficiency and safety of road construction. The system uses a combination of sensors, drones, and machinery vehicles to collect data about the road construction site in real time. This data is then used to create a digital twin of the road, which can be used to plan and execute construction activities more effectively. The system can also be used to monitor the progress of construction and identify potential problems early on.

@startuml

actor User

User -> DTInterface: Access scheduled program

activate DTInterface

DTInterface -> T4.1: Activate drone

activate T4.1

T4.1 -> Drone: Perform initial photogrammetry

activate Drone

Drone -> DTInterface: Update initial surface photogrammetry

deactivate Drone

DTInterface -> MachineryVehicles: Send instructions based on real-time data from sensors

activate MachineryVehicles

MachineryVehicles -> DTInterface: Send status updates to monitor progress and detect anomalies

deactivate MachineryVehicles

DTInterface -> AnalyticsEngine: Detect anomalies in road construction progress through real-time data analytics.

activate AnalyticsEngine

AnalyticsEngine --> DTInterface: Return anomaly detection results.

deactivate AnalyticsEngine

activate Drone

Drone -> DTInterface: Perform final photogrammetry

@enduml

Use Case 5: Building Construction

This use case describes how the BEEYONDERS system can be used to improve the efficiency and safety of building construction. The system uses a combination of sensors, drones, and machinery vehicles to collect data about the building construction site in real time. This data is then used to create a digital twin of the building, which can be used to plan and execute construction activities more effectively. The system can also be used to monitor the progress of construction and identify potential problems early on.

@startuml

actor DesignTeam

actor DronePilot

actor FieldWorker

actor ProjectLeader

actor DigitalTwin

actor SensorInstaller



DesignTeam -> DigitalTwin: Request access to BIM-based interface

DigitalTwin -> DesignTeam: Grant access to BIM-based interface

DronePilot -> DigitalTwin: Upload 3D map of construction site

DigitalTwin -> FieldWorker: Provide access to safety training, task assignments, schedules, productivity checks, and reflectivity analysis in real-time

FieldWorker -> DigitalTwin: Access safety training, task assignments, schedules, productivity checks, and reflectivity analysis in real-time

DigitalTwin -> ProjectLeader : Provide real-time visibility into worker location, task progress,equipment status ,and safety data

ProjectLeader -> DigitalTwin : Request real-time visibility into worker location, task progress,equipment status ,and safety data

SensorInstaller -> DigitalTwin : Provide specifications for sensor installation

FieldWorker -> DataScientist : Provide data captured from drones, wearables,and exoskeletons

DataScientist -> FieldWorker : Develop algorithms/models that allow field users perform their tasks efficiently and safely

DigitalTwin-> ProjectOwnerDeveloper : Provide access to data on construction progress ,quality, costs ,environmental impact in real-time

ProjectOwnerDeveloper-> DigitalTwin : Request access to data on construction progress ,quality, costs ,environmental impact in real-time

@enduml

Use case 3: Maritime Construction

This use case describes how the BEEYONDERS system can be used to improve the efficiency and safety of maritime construction. The system uses a combination of sensors and machinery vehicles to collect data about the maritime construction site in real time. This data is then used to create a digital twin of the maritime construction site, which can be used to plan and execute construction activities more effectively. The system can also be used to monitor the progress of construction and identify potential problems early on.

@startuml

actor PortAuthority

actor ConstructionManager

actor StructuralEngineer

actor EnvironmentalScientist

actor ProjectManager

database DTdatabase

participant SEABOOST

participant CAIDIO



[D3.1: Digital Twin Design and Architecture]

participant BIMInterface

participant WaveHarvestingEquipmentProvider

participant BiocompatibilityMortarProvider

PortAuthority -> ProjectManager: Request project updates

ProjectManager -> ConstructionManager: Provide project updates

ConstructionManager -> DTdatabase: Request real-time data on construction site and equipment status

DTdatabase -> ConstructionManager: Provide real-time data

StructuralEngineer -> SEABOOST: Request sensor data from caisson structure

SEABOOST -> DTdatabase: Retrieve sensor data from environmental sensors

DTdatabase -> StructuralEngineer: Provide sensor data

EnvironmentalScientist -> SEABOOST: Request water quality and marine life updates around construction site

SEABOOST -> DTdatabase: Retrieve water quality and marine life data from environmental sensors

DTdatabase -> EnvironmentalScientist: Provide water quality and marine life data

CAIDIO -> DTdatabase: Request IoT sensor data for material production analysis calculations

DTdatabase -> CAIDIO: Provide IoT sensor data for material production analysis calculations

ProjectManager -> BIMInterface : Request 3D point cloud visualization of finished caisson before submerging

BIMInterface --> ProjectManager : Provide 3D point cloud visualization of finished caisson before submerging

ProjectManager --> WaveHarvestingEquipmentProvider : Request installation of wave harvesting equipment on caisson structure (optional)

WaveHarvestingEquipmentProvider --> ProjectManager : Confirm installation of wave harvesting equipment on caisson structure (optional)

ProjectManager --> BiocompatibilityMortarProvider : Request application of reef growth promoting coat on caisson structure

BiocompatibilityMortarProvider --> ProjectManager : Confirm application of reef growth promoting coat on caisson structure

@enduml

Use Case 4: Maritime Construction (Japan)

This use case describes how the BEEYONDERS system can be used to improve the efficiency and safety of maritime construction in collaboration with Japan. The system uses a combination of sensors and machinery vehicles to collect data about the maritime construction site in real time. This data is then used to create a digital twin of the maritime construction site, which can be used to plan and execute construction activities more effectively. The system can also be used to monitor the progress of construction and identify potential problems early on.

@startuml

actor "Port of Rotterdam authorities" as port

actor "Design team" as design

actor "Digital Twin" as twin

actor "Field worker" as worker

actor "Project leader" as leader

actor "Project owner" as owner

actor "Sensor installer" as installer

port -> twin: Collect geotechnical data\nand deposit into DT database

twin -> twin: Generate 3D model\nof testing area



[D3.1: Digital Twin Design and Architecture]

worker -> twin: Install sensors on site\nto collect geotechnical data

twin -> worker: Provide instructions\nfor sensor installation

worker -> twin: Send collected data\nto DT database via gateway connection

design -> twin: Access geotechnical data\nfrom DT database

twin -> design: Provide updated geological\ndigital twin with accurate information

leader -> twin: Access predictions based on estimation of ground capacity and piling installation optimization results

twin -> leader: Provide predictions based on estimation of ground capacity and piling installation optimization results

owner -> twin: Obtain economical and environmental KPIs from optimization results

twin -> owner: Provide economical and environmental KPIs from optimization results

installer --> twin : Receive clear instructions on how to install sensors correctly

@enduml

Use Case 6: Road Maintenance

This use case describes how the BEEYONDERS system can be used to improve the efficiency and safety of road maintenance. The system uses a combination of sensors, drones, and machinery vehicles to collect data about the road maintenance site in real time. This data is then used to create a digital twin of the road, which can be used to plan and execute maintenance activities more effectively. The system can also be used to monitor the progress of maintenance and identify potential problems early on.

@startuml

actor "Design Team" as DT

actor "Drone Pilot" as DP

actor "DT Manager" as DTM

actor "Field Worker" as FW

participant "Digital Twin" as DTW

actor "Project Leader" as PL

actor "Project Owner/Sponsor" as POS

actor "Sensor Installer" as SI

DT -> DTW: Design autonomous inspection vehicle

DP -> DTW: Fly drone over road to deploy inspection vehicle safely and efficiently

DTM -> DTW: Manage permits for flying drones and deploying inspection vehicles

FW -> DTW: Use autonomous robotics to perform inspections more efficiently and safely than traditional methods

SI -> DTW: Install sensors on infrastructure elements such as traffic signals in a way that is compatible with autonomous robotics for future inspections

activate DTW

DTW -> DT: Provide visualization of road infrastructure elements such as traffic signals and vegetation growth in real-time

DTW -> DP: Provide data on optimal flight paths for drone inspections based on real-time conditions and analysis of previous flights

DTW -> DTM: Provide data on permit status and flight paths for drone inspections to ensure compliance with regulations and safety protocols



[D3.1: Digital Twin Design and Architecture]

DTW -> FW: Provide data on optimal routes for autonomous inspection vehicle based on real-time conditions and analysis of previous inspections

DTW -> SI: Provide data on optimal sensor placement based on analysis of previous inspections

activate PL

PL -> DT: Monitor progress of project, including workflow management, cost optimization, and stakeholder communication

deactivate all

@enduml

Use Case Common: Construction Project Management

This use case describes how the BEEYONDERS system can be used to improve the efficiency and safety of construction project management. The system uses a combination of sensors, drones, and machinery vehicles to collect data about the construction project site in real time. This data is then used to create a digital twin of the construction project site, which can be used to plan and execute construction activities more effectively. The system can also be used to monitor the progress of construction and identify potential problems early on.

@startuml

title BEEYONDERS Construction Project Management System

actor ProjectSupervisor as ACCIONA

actor ConstructionProjectManager as CPM

actor SiteManager as SM

actor MachineryVehicleOperator as MVO

actor DroneOperator as DO

actor EnvironmentalSpecialistHealthSafetyOfficer as ESHSO

actor DataEngineer as DE

actor DataAnalyst as DA

actor MachineLearningEngineer as MLE

actor ITAdministrator as ITA

actor DigitalTwin as DT

CPM -> DT: Provide specifications and requirements for the digital twin to ensure that the virtual replica matches the physical design

SM -> DT: Use the digital twin to plan and execute construction activities

MVO -> DT: Provide information (position, orientation, cloud points, distances) through sensors to update the digital twin model

DO -> DT: Collect accurate data from drones for use in various types of construction projects

ESHSO -> DT: Analyze CO2 emissions savings and fuel consumption data collected by the system or SMW interaction detection to AWL / Health & Safety (H&S) from worker measures data collected by the system



DE -> DT: Create and maintain ETL pipelines and load data into the datalake

DA -> DA: Explore and analyze large datasets

MLE -> MLE: Experiment with different algorithms and hyperparameters

ITA -> ITA: Manage the cloud data service and ensure that it is secure, reliable, and scalable

ACCIONA -> SM: Receive and provide information to the system

@enduml

Hybrid Architecture Diagram

This diagram illustrates the hybrid architecture of the BEEYONDERS system. The system is composed of a combination of cloud-based and on-premise components. The cloud-based components provide scalability and reliability, while the on-premise components provide security and control.

The following are the key components of the hybrid architecture:

- Cloud-based components:
 - Azure Data Lake System: A scalable and reliable data storage and processing platform.
 - Databricks: A cloud-based platform for data engineering and machine learning.
 - Virtual Machines: A scalable and reliable computing platform.
- On-premise components:
 - InfluxDB: A time series database.
 - PostgreSQL: A relational database.
 - NodeRED: A flow-based programming tool.
 - MQTT Broker: A message broker.
- Security:
 - Firewall: A network security device that filters incoming traffic.
 - Encryption: A security mechanism that protects data in transit and at rest.
 - Access control mechanisms: A set of policies that restrict access to resources.
 - Monitoring tools: A set of tools that detect and alert on security incidents.
- Sensor Platform:
 - Sensors and Autonomous Vehicles: Devices that collect data from the physical world.
 - Wearables: Devices that can be worn by people.
 - Exoskeletons: Devices that can be worn by people to augment their strength and mobility.

The BEEYONDERS system uses a combination of cloud-based and on-premise components to provide a scalable, reliable, secure, and controlled platform for collecting, storing, processing, and visualizing data from construction sites. The system can be used to improve the efficiency and safety of construction projects by providing real-time insights into the construction process.

@startuml

title BEEYONDERS Hybrid Architecture Diagram



actor User

User -> LoadBalancer : Sends requests

```

rectangle "Cloud Service / On-premise Provider" #Application {
  rectangle "Azure DataLake System"
  rectangle "Databricks"
  rectangle "VirtualMachines" {
    rectangle "InfluxDB"
    rectangle "PostgreSQL"
    rectangle "NodeRED"
    rectangle "MQTTBroker"
  }
  LoadBalancer -> VirtualMachines : Distributes traffic
  InfluxDB <-> NodeRED
  MQTTBroker <-> NodeRED : Collects data from sensors
}

```

```

rectangle "Knowledge Base" #Physical {
  rectangle "KnowledgeBase"
  PostgreSQLSystem -> KnowledgeBase : Stores models
  InfluxDBSystem -> KnowledgeBase : Stores real-time data
  AzureDataLakeSystem -> KnowledgeBase : Stores historical data
  DatabricksSystem -> KnowledgeBase : Processes large amounts of data in parallel
  NodeREDSystem -> AzureDataLakeSystem : Push data to DataLake
}

```

```

rectangle "User Interface Layer" #Implementation {
  User -> WebServer : Sends requests
  WebServer -> VirtualMachine : Retrieves and displays data
}

```

```

rectangle "Security" #Motivation {
  Firewall -> VirtualMachine : Filters incoming traffic
  Encryption -> VirtualMachine : Secures data in transit and at rest
  AccessControlMechanisms -> VirtualMachine : Restricts access to resources
  MonitoringTools -> VirtualMachine : Detects and alerts on security incidents
}

```

```

rectangle "Sensor Platform" #Business {
  rectangle "Sensors"
  rectangle "Wearables"
  rectangle "Exoskeletons"
  Sensors --> Wearables
  Wearables --> Exoskeletons
  Exoskeletons --> SensorPlatform
  SensorPlatform --> MQTTBroker: Sends sensor, wearables, and exoskeletons data to middleware layer
}

```



