A Holistic Digital Mine 4.0 Ecosystem

D2.1
Functional and Non-Functional Requirements in the Digitisation of the Mining Sector – Version 1

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Deliverable	D2.1 – Functional and Non-Functional Requirements in the Digitisation of the Mining Sector – Version 1
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Abstract	The deliverable D2.1 describes all project Pilot Sites and their Technology Partners. For each Pilot Site, different technologies are developed, implemented and validated. The tasks in each Pilot Site are specified and listed together with the Technology Partners. Subsequently, the functional and non-functional requirements are defined by the Pilot Sites. The Pilot Sites and their technologies are analysed with regard to their socio-economic aspects.
Disclaimer	

History of Changes

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V0.1	29/06/2023	Initial Table of Contents for discussion in the Athens general assembly meeting	TUB
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EXECUTIVE SUMMARY

The Mine.io project is divided into two parts. On the one hand, different technologies are developed and tested at seven Pilot Sites. On the other hand, one of the goals is to develop a common architecture for the digitisation of mining. Structuring principles will be provided to drive the integration of different technological solutions from Mine.io into an end-to-end mining application. This deliverable (Deliverable 2.1, i.e., D2.1) introduces the various Pilot Sites and their technologies and requirements. At the beginning of the project, the Pilot Sites and Technology Partners were brought together and the tasks at the respective Pilot Sites were defined. In the next step, the functional and non-functional requirements of the Pilot Sites for the technologies were established. The next version of the document will add the requirements of the Technology Partners.

Pilot Site 1 is divided into two different units at the technical university of Freiberg, Germany. The research and teaching mine Reiche Zeche is titled Pilot Site 1.1. Two digitalisation tasks will be done during the Mine.io project at this mine. The first deals with installing sensors with a data logger on an existing core drilling rig and a subsequent task of evaluating the data with AI. For the second task, a digital twin of the mine ventilation shall be developed. This includes reviewing and installation of multiple sensors. The second Pilot Site 1.2, also in Freiberg, is located at the Institute of Nonferrous Metallurgy. The Top Submerged Lance (TSL) smelter will demonstrate the use of a range of sensor techniques combined with simplified embedded models derived from Computational Fluid Dynamics (CFD) calculations and on-line process models (digital twins).

Pilot Site 2 is located in Polkowice, Poland, in the KGHM Mineral Processing Plant. The most important technological process in this place is the flotation process. The Photonic-IT (PIT) System will be installed and tested on one of the flotation cells in this plant.

Pilot Site 3 is located at the Lavrion Technological & Cultural Park in Greece. The dry tomb (mining waste repository) will be analysed, including optimal area characterisation and obtaining valuable and exploitable information on soil composition and distribution (exploration) in order to propose a valuable metal extraction method (extraction) and/or propose a management/ remediation method for pilot application (waste management).

Pilot Site 4 is located at the Pyhäsalmi mine in Finland. The objective is to pilot a geophysical approach for monitoring the subsurface condition of tailings embankments. A combination of electrical resistivity imaging (ERI) and active and passive seismic imaging will be developed and applied to map the subsurface structure of the tailings dam and to retrieve hydrogeological and elastic parameters.

Pilot Site 5 is located at the Erzgebirgische Fluss- und Schwerspatwerke GmbH (EFS) mine in Niederschlag, Germany. There will be developed and implement an underground mobility solution for electric-driven battery vehicles and autonomous driving functions in underground trucks. This includes the integration of the electrification paradigm with the development of necessary charging parameters for electric-driven vehicles and the automatic docking system to the inductive loops.

Pilot Site 6 is represented by two sites, both are located in Portugal; these are the Malaposta open pit near Porto and the Urgeiriça mine near Viseu. In these sites, a muon imaging and monitoring instrument designed for mining applications, as well as an underwater vehicle specifically engineered for in-situ exploration in flooded mines, will undergo rigorous testing and validation.

TABLE OF CONTENTS

LIST OF FIGURES

TERMS AND ABBREVIATIONS

AI	-	Artificial Intelligence
ACT	-	Advanced Control Technology
API	-	Application Programming Interface
AUV	-	Autonomous Underwater Vehicle
AutoML	-	Automated Machine Learning
CFD	-	Computational Fluid Dynamics
D	-	Deliverable
DT	-	Digital Twin
DTM	-	Digital Terrain Model
DWCS	-	Dynamic Wireless Charging Solution
EDM	-	Express Data Manager
EMF	-	Electric Magnetic Field
ERI	-	Electric Resistivity Imaging
FE	-	Functional Entities
FMCW	-	Frequency-Modulated Continuous Wave Radar
FTIR	-	Fourier Transform Infrared Spectrometry
GLC	-	Geosynthetic Clay Liner
GNSS	-	Global Navigation Satellite System
GPU	-	Graphics Processing Unit
GUI	-	Graphical User Interface
HDPE	-	High-density Polyethylene
HSC	-	Enthalpy, Entropy, Compare: heat capacity
IEEE	-	Institute of Electrical and Electronics Engineers
IIoT	-	Industrial Internet of Things
IoT	-	Internet of Things
ISO	-	International Organization for Standardization
LCA	-	Life Cycle Assessment
LIBS	-	Laser-Induced Breakdown Spectroscopy
LiDAR	-	Light Detection and Ranging
LTCP	-	Lavrion Technological & Cultural Park
ML	-	Machine Learning
MWD	-	Measurement While Drilling
NN	-	Normalnull “standard zero”
OBD	-	On-Board-Diagnosis standard
OMS	-	Oulu Mining School
OSD	-	Onboard Sending Device
PIT	-	Photonic-IT (PIT) System
PLM	-	Product Lifecycle Management
REST	-	Representational State Transfer
RGB	-	Red, Green, Blue
T	-	Task
TSL	-	Top Submerged Lance Furnace
UC	-	Use Case
VDSC	-	Vehicle Detection and Section Control
WP	-	Work Package

XAI	-	eXplainable Artificial Intelligence
ZWR	-	Zakłady Wzbogacania Rud (Ore enrichment plants)

Abbreviations of the companies participating in Mine.io

ACC	-	ACCELIGENCE LtD
AGH	-	AGH University of Science and Technology
AMDC	-	Etaireia Axiopoiiseos kai Diacheiriseos tis Periousias tou Ethnikou Metsoviou Polytechneiou
EFS	-	Erzgebirgische Fluss- und Schwerspatwerke GmbH
ENRX	-	ENRX GmbH (former IPT technology)
FhG	-	Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V.
FRON	-	Frontier Innovations
GFT	-	GFT ITALIA SRL
HMU	-	Hellenic Mediterranean University
ICCS	-	Institute of Communication and Computer Systems
INE	-	INESC TEC - Institute for Systems and Computer Engineering, Technology and Science
INN	-	Innov-Acts Limited
JOT	-	Jotne Connect
KGHM	-	KGHM Polska Miedź SA
Ł-EMAG	-	Łukasiewicz Research Network – Institute of Innovative Technologies EMAG
Ł-ITR	-	Łukasiewicz Research Network – Tele and Radio Research Institute
LTU	-	Lulea University of Technology
MUO	-	Muon Solutions
POL	-	Politecnico di Torino
TEC	-	Fundacion Tecnalia Research & Innovation
TUB	-	Technische Universität Bergakademie Freiberg
UGR	-	Unexmin GeoRobotics
UOULU	-	University of Oulu
USAL	-	University of Salamanca
WRCP	-	Wigner Research Centre for Physics

ADDITIONAL DEFINITIONS

Description of Action:
The Grant Agreement is the funding agreement signed between the European Commission and the Beneficiary. It contractually regulates the implementation of the project and specifies important provisions such as criteria for the eligibility of costs, reporting, payments, and deadlines. The Description of the Action is Annex 1 of the Grant Agreement and is a detailed description of how the project will be carried out. It comprises Part A & B and both parts can be edited on the Funding & Tenders Portal. (Polite, 2023)

Edge-to-Cloud:
In the context of Mine.io, "Edge-to-Cloud" refers to a computing architecture that facilitates the seamless transfer of data from edge devices, such as IoT sensors deployed in mining operations, to a centralised cloud-based storage and processing system. The implementation hinges on the existing or planned network infrastructure within the mine. A key element in this architecture is the IIoT gateway, which serves as the conduit for transmitting data collected from various IoT devices and other sources to the Cloud. This approach aims to optimise data management, analytics, and decision-making processes, thereby enhancing operational efficiency and strategic planning in mining activities.

Functional and non-functional requirements:
In the context of Mine.io, "functional requirements" refer to the essential tasks, behaviours, and operations that a system, machinery, sensor, or geophysical instrument must perform. These are the core functionalities that enable the system to meet its intended objectives. On the other hand, "non-functional requirements" pertain to the quality attributes that a system, organisation, or service must possess, such as scalability, reliability, and performance. Within the same framework, this could encompass aspects like the durability of equipment and energy efficiency. Both functional and non-functional requirements are integral to the overall effectiveness and sustainability of mining operations, and they often complement each other to ensure a holistic approach to project execution.

Live Document:
In the context of Mine.io, “live document” refers to a document that is currently being edited collaboratively and in real-time. The editing is closed before the Mine.io project ends.

Technology Partner:
In the context of Mine.io, a "Technology Partner" refers to an organisation or entity that collaborates with the project to provide cutting-edge technological solutions specifically tailored for the mining industry. These partners are responsible for the development, implementation, and testing of novel technologies that aim to enhance various aspects of mining operations, such as excavation, extraction, waste management, and digitisation. Within the framework of the Mine.io project, Technology Partners play a pivotal role in advancing the project's objectives by deploying their innovations at designated Pilot Sites for empirical validation. These Pilot Sites serve as real-world testing grounds where the efficacy, scalability, and adaptability of the provided technologies are rigorously evaluated. The ultimate goal is to integrate these technological advancements seamlessly into the existing

mining ecosystem, thereby contributing to the project's overarching aims of operational efficiency, sustainability, and holistic management.

1. INTRODUCTION AND OBJECTIVES

1.1 PURPOSE AND SCOPE

The project Mine.io demonstrates the vision of the future digital mine. In the project, there are many different technologies that are being developed and tested on seven Pilot Sites. This document shall specify in detail the holistic approach to digitalising the mining sector and how existing technologies can be utilised for this purpose. Therefore, it has to address socio-technical factors as well as the modular approaches. The Deliverable 2.1 is a live document during the project and will be submitted in two versions. This will allow for constant expansion as well as adjustments of the document and improvement of the information on the current state of development.

At the beginning of the project, the various Pilot Sites were on one side and the technology providers on the other. Due to the Grant Agreement, the first linkage points are predetermined. In the first months, the Pilot Sites and the technology providers were brought together. All partners specified the tasks and created the requirements. The present document contains information on all Pilot Sites and their technologies. It is structured along the lines of the Grant Agreement signed by all partners. This means that the chapters are named after the respective technologies to be developed. The structure is based on the Pilot Sites that test the different superordinate technology. If technologies of the same group are tested in different Pilot Sites, they are summarised in a superordinate chapter and then specified.

For each Pilot Site, an overview of the mine, plant or tailings is provided. The technologies to be tested, together with the associated partners, are presented. For each Pilot Site, the different partners were brought together in the first months and detailed tasks of the technologies to be tested were listed. The requirements were derived from these tasks. The first version of D2.1 focuses on the requirements of the respective Pilot Site for the technologies to be tested, and these are then defined for each Pilot Site.

The definition of requirements is essential, serving as foundation of every successful project. The requirements establish a mutual understanding between the Pilot Sites and the Technology Partners, ensuring that they are aligned in pursuit of the same goal. Defining requirements is crucial for minimizing the risk of problems arising later in the tasks and project. Creating high-quality requirements is a complex task that requires continuous attention from the beginning of the project.

Several templates were created to gather all the necessary information from both the Pilot Sites and Technology Partners. The first table provides an overview of all the Pilot Sites, integrating their related fundamentals, digitisation strategies, and key factors. The second template is individual for all Pilot Sites. The various tasks of the Pilot Sites are described and specified together with their Technology Partners. After defining the individual tasks, a template was created to collect functional and non-functional requirements for the specific tasks. This template provides an overview of the Pilot Sites' requirements for the Technology Partners.

Another template is the Inventory List. It collects all software and hardware components used in the project. This list is available as part of a spreadsheet and is constantly maintained as a live document. All components that are included in this document are also fundamental for achieving a standardisation approach. Chapter 1.4 gives an overview of the inventory list and the standardisation process.

1.2 Deliverable Methodology and Structure

In D2.1, a chapter is dedicated to each use case with its associated technologies, specifically addressing the current approach. These chapters will be continuously updated in the sense of versioning as the project consortium's knowledge progresses. In the beginning, however, only the state of the art based on literature as well as the previously accumulated knowledge of the researchers can be used. The structure follows the use cases and the associated technologies.

- Chapter 1 provides an introduction and overview of the Deliverable 2.1.
- Chapter 2 introduces Pilot Site 5, which is the Niederschlag mine, owned by Erzgebirgische Fluss- und Schwerspatwerke GmbH (EFS).
- Chapter 3 presents three Pilot Sites: Pilot Site 1.1, located at the Technical University Bergakademie Freiberg, focuses on the research and education mine Reiche Zeche; Pilot Site 1.2, also situated at TU Bergakademie Freiberg, involves the Top Submerged Lance (TSL) furnace at the Institute of Nonferrous Metallurgy; and Pilot Site 2, based at the KGHM Mineral Processing Plant, works on the digital flotation system.
- Chapter 4 presents two Pilot Sites in Portugal: Pilot Site 6 has two locations the Malaposta open pit site and the Urgeiriça mine. The Institute for Systems and Computer Engineering, Technology and Science (INESC TEC) organises the work at this site.
- Chapter 5 presents 2 Pilot Sites: logistics at Pilot Site 3, which is located in Lavrion, Greece, are arranged by the Lavrion Technological and Cultural Park; Pilot Site 4 is a deep underground mine located at Pyhäsalmi in Central Finland. Any work carried out in the latter is guided by the University of Oulu, Finland.

Since the Pilot Sites themselves know best which research and technological developments need to be done or implemented to be both more effective and more ecological, the Pilot Sites are the stakeholders who need to be addressed within the WP2. The second group of stakeholders consists of technology developers who have already been in close contact to discuss potential projects.

Consequently, D2.1 explicitly focuses on the technologies previously outlined in the project proposal. These technologies are scheduled for testing within the confines of the designated Pilot Sites. This strategy allows research to be conducted from the outset towards the use cases, thus directly excluding non-functional approaches for the future pilot case.

1.3 Relation to Other WPs/Tasks

The Deliverable 2.1 describes several tasks of WP2 of the project, notably:

- "T2.1 Europe-wide geographical and socio-economic conditions and contexts in raw materials".
- "T2.2 Exploration, electrification and extraction understanding and technical requirement".
- "T2.3 Processing and waste management understanding and technical requirement".
- "T2.4 Mine sector digitisation understanding and technical requirement".
- "T2.6 Inventory list of software, hardware, standards and use case data".

The Deliverable 2.1 provides important input to the technical WPs of the project (especially WPs 3, 4 and 5). The definition of the technologies to be tested at the Pilot Sites is the basis for further work within the project. The defined functional and non-functional requirements form the initial basis for the development of the technologies.

1.4 Standardisation Approach for Holistic Digitisation in Mining

Under T2.6, an inventory list is used to achieve the objective of holistic digitisation in mining. As per ISO 23247 (International Organization for Standardization, 2021), Digital Twin (DT) adaptation is based on the successful implementation of standards and its methods. To achieve this, an inventory list is created to collect the components involved in the DT creation of the product or processes in this project.

The inventory list adapts the concept of functional entities based on ISO 23247, where Digital Twin architecture references entity-based model and functional view. The DT framework breaks down into systems and subsystems according to the entity-based reference model. The functional view identifies functionalities that are referred to as functional entities (FE) for each of these sub-systems or components involved in building DT. (International Organization for Standardization, 2021)

With reference to the DT framework, an inventory list template has been established that collates details of functional entities involved in this project. These entities includes Hardware, Software, AI, IoT, Data sharing and infrastructure, Test Data, Sensors, Standards, Cloud services, Engineering Tools and Network Components, as illustrated in Figure 1.

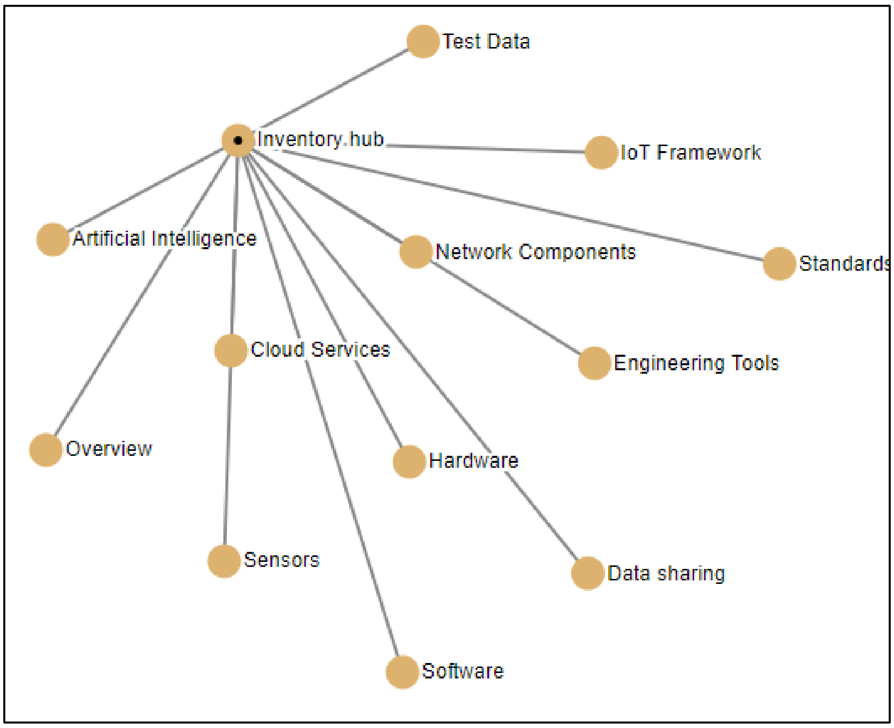

Figure 1 Functional Entities for DT Framework

These entities are then stored in the ISO 10303 standard repository, which is EDMtruePLM; a cloud capable IoT repository with data storage, exchange & archiving capabilities. It will be used as a centralized repository to store all the use case related data and also to create digital representations of the tools involved as shown in Figure 2. The virtual flow of tools and technologies can be seen in the below snapshots Figure 3 and Figure 4. The use of a standards data storage tool supports standardised approaches for the design and successful implementation of the Digital Twin system in the Mine.io project.

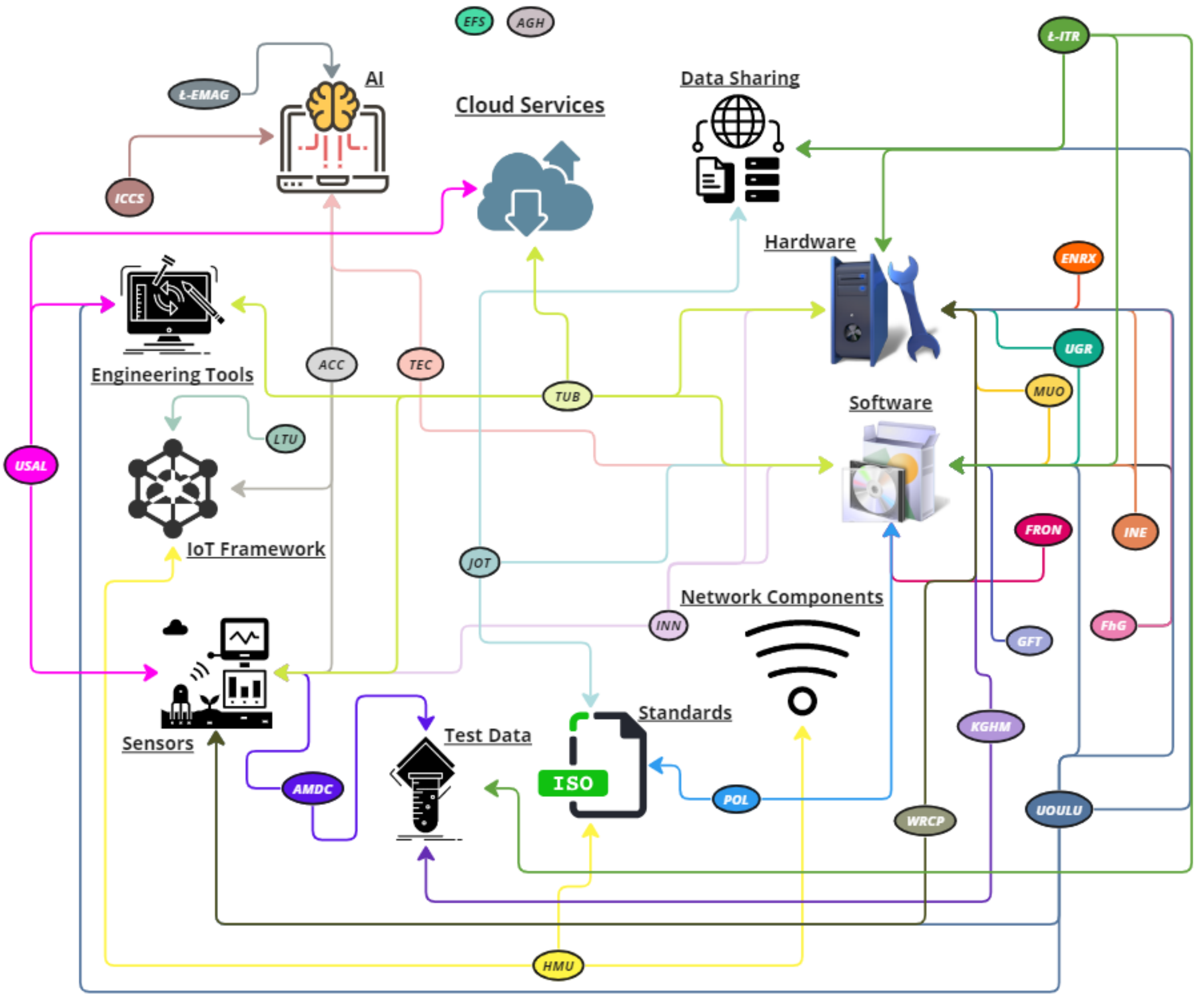

Figure 2 Overview of Inventories for Mine.io Platform

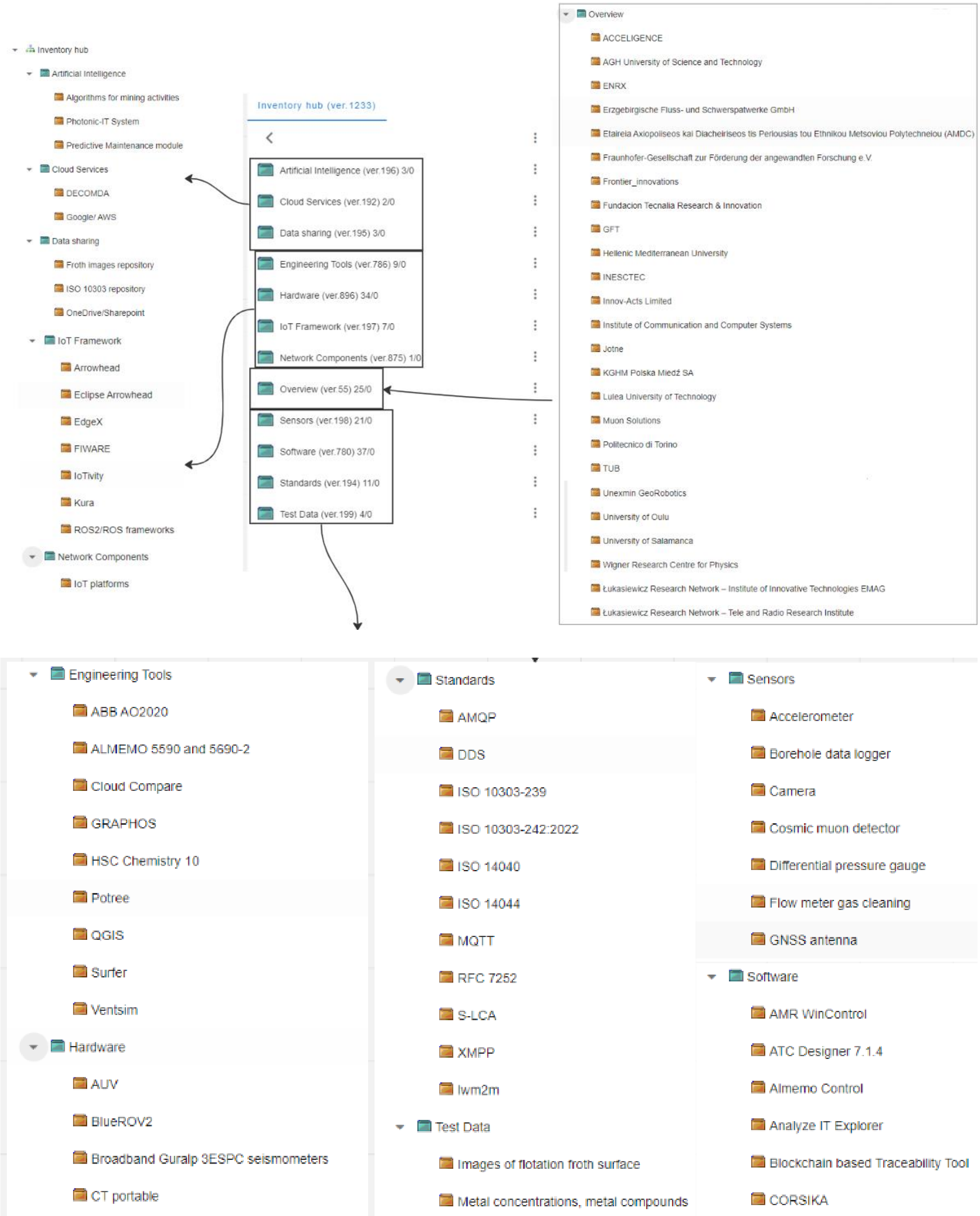

Figure 3 Overall Inventory List Representation in EDMtruePLM

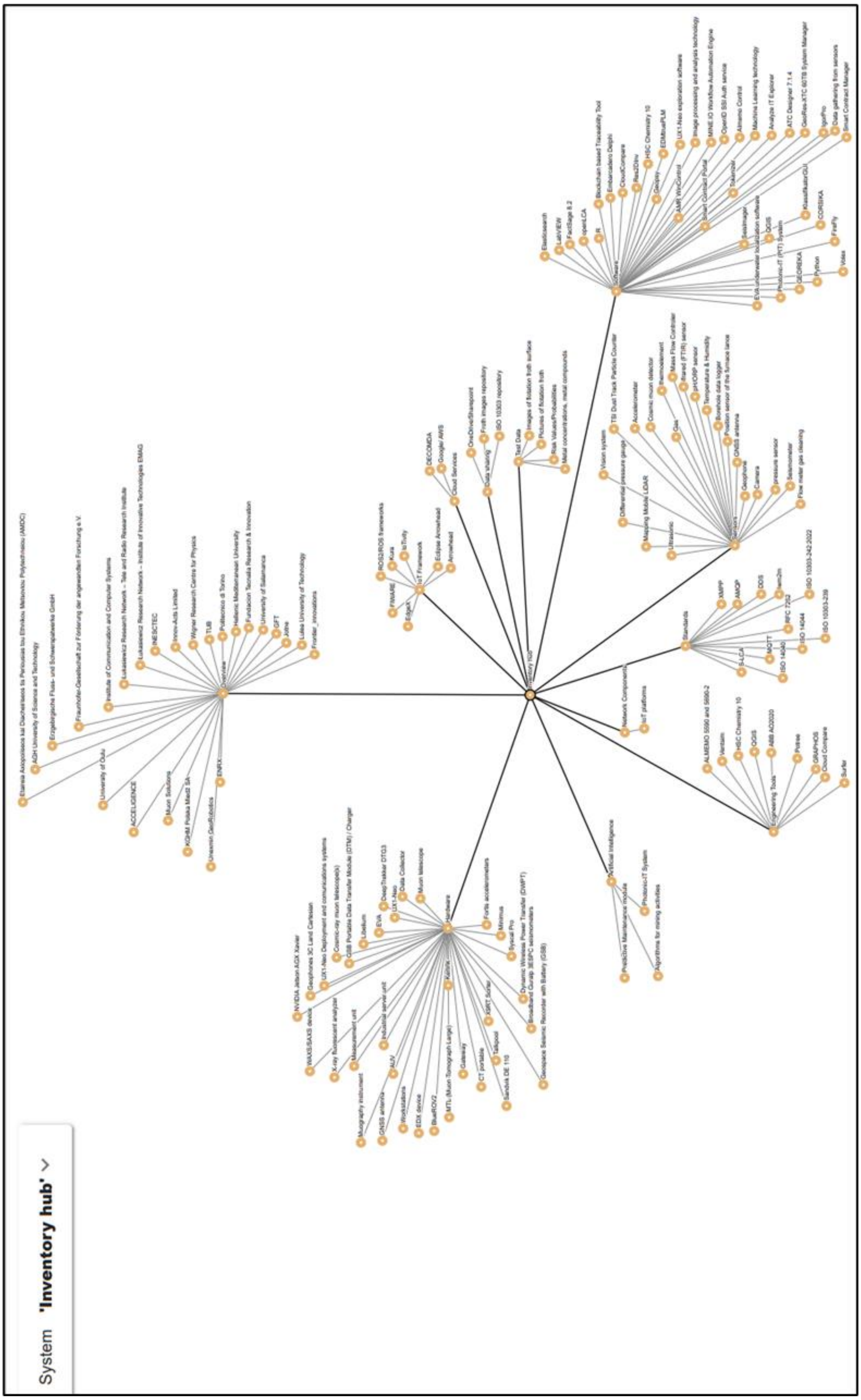

Figure 4 Tree View

In the subsequent Figure 5, Figure 6 and Figure 7, the properties of individual components can be visualised. For example, within the Hardware category, specific details of the GNSS antenna are presented. For instance, one can observe information relating to the model, description, and responsible partner (Figure 5).

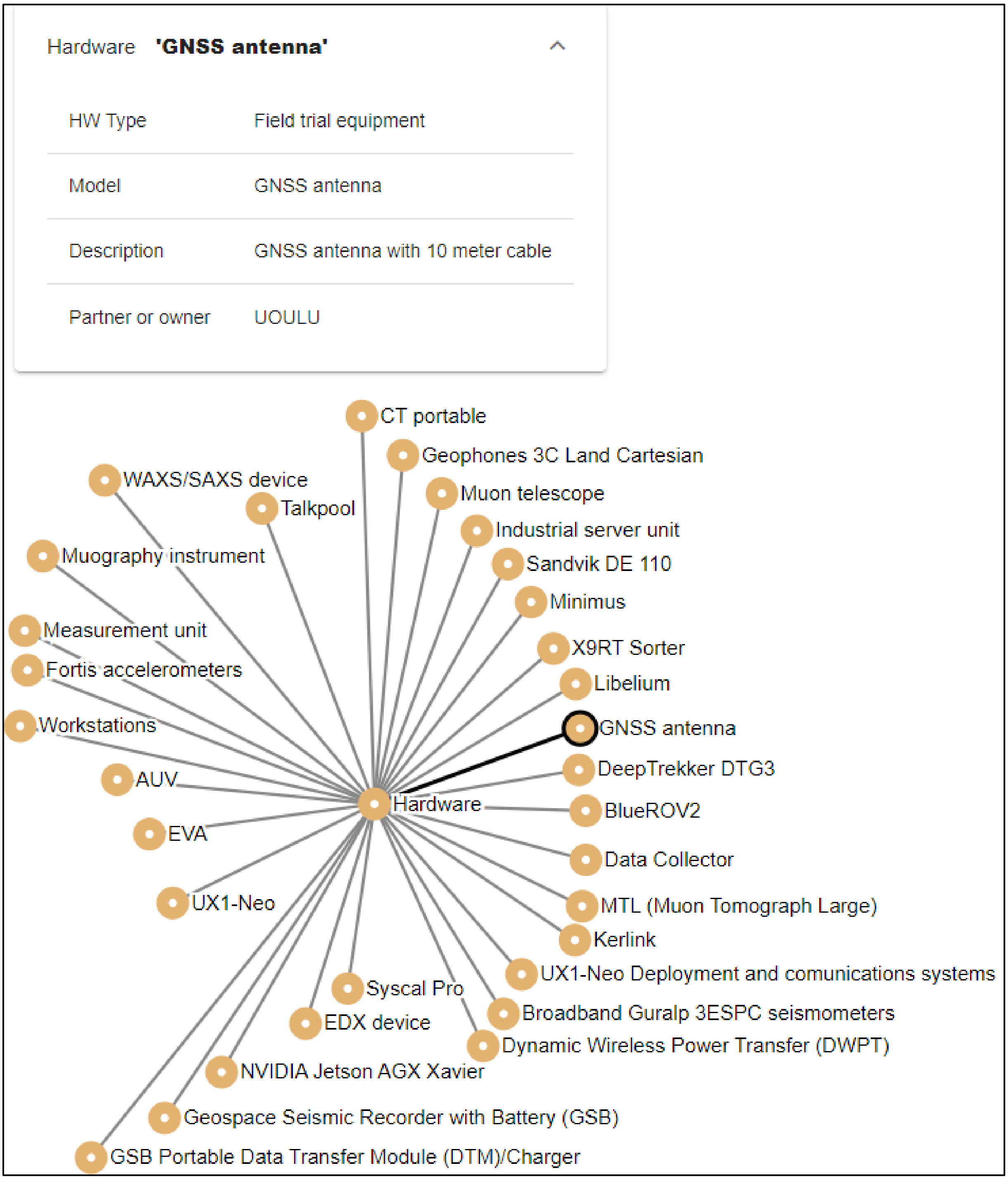

Figure 5 Hardware involved in Mine.io

Software **'FireFly'**

SW Type	Software to reconstruct threedimensional volumes of Xray scans
Name	FireFly
Description	Software to process Xray projections and create Xray 3D-volumes
Operating System	Windows
Input	Radiographic projections
Output	reconstructed three-dimensional volume of scanned object
Partner or owner	Fraunhofer IIS EZRT

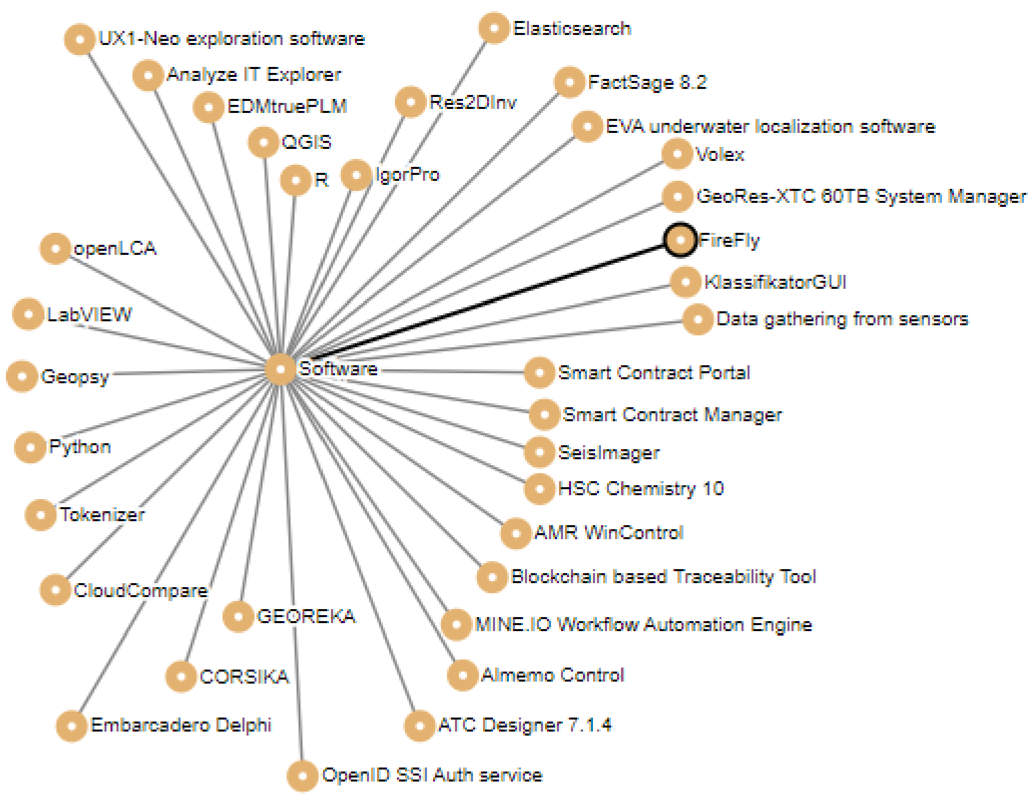

Figure 6 Software list

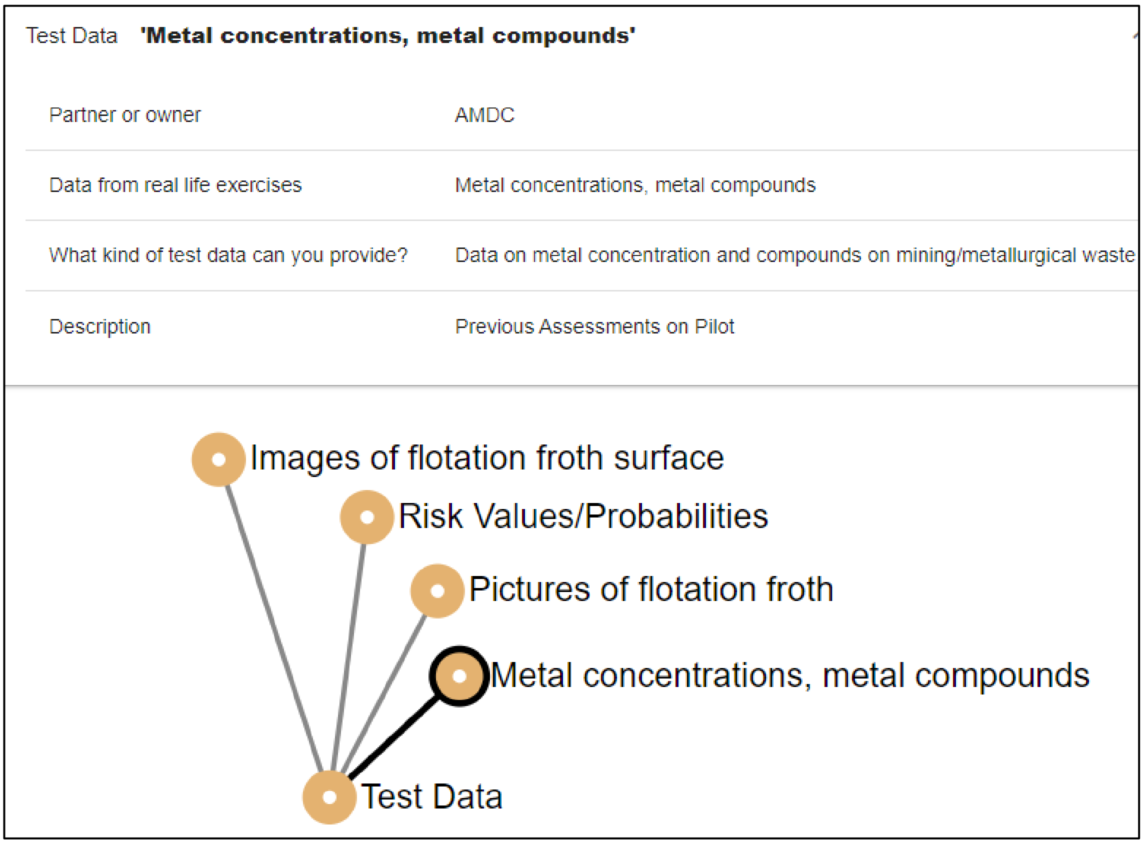

Figure 7 Test Data information

During the initial phase of the Mine.io project, available information from the inventory list will be used to validate the use cases involved in this project to support the DT approach. The EDMtruePLM Module, for example, can be used to store the sensor data, such as from the smelter at the TUB mine in Germany, i.e. the Reiche Zeche mine. The smelter will be integrated with the EDMtruePLM Module using the REST API/Arrowhead framework of the client front-end. User access, project details and product structure will be created through the Web GUI; sensor data, on the other hand, can be populated using IoT integration.

Figure 8 illustrates an example of the use case flow:

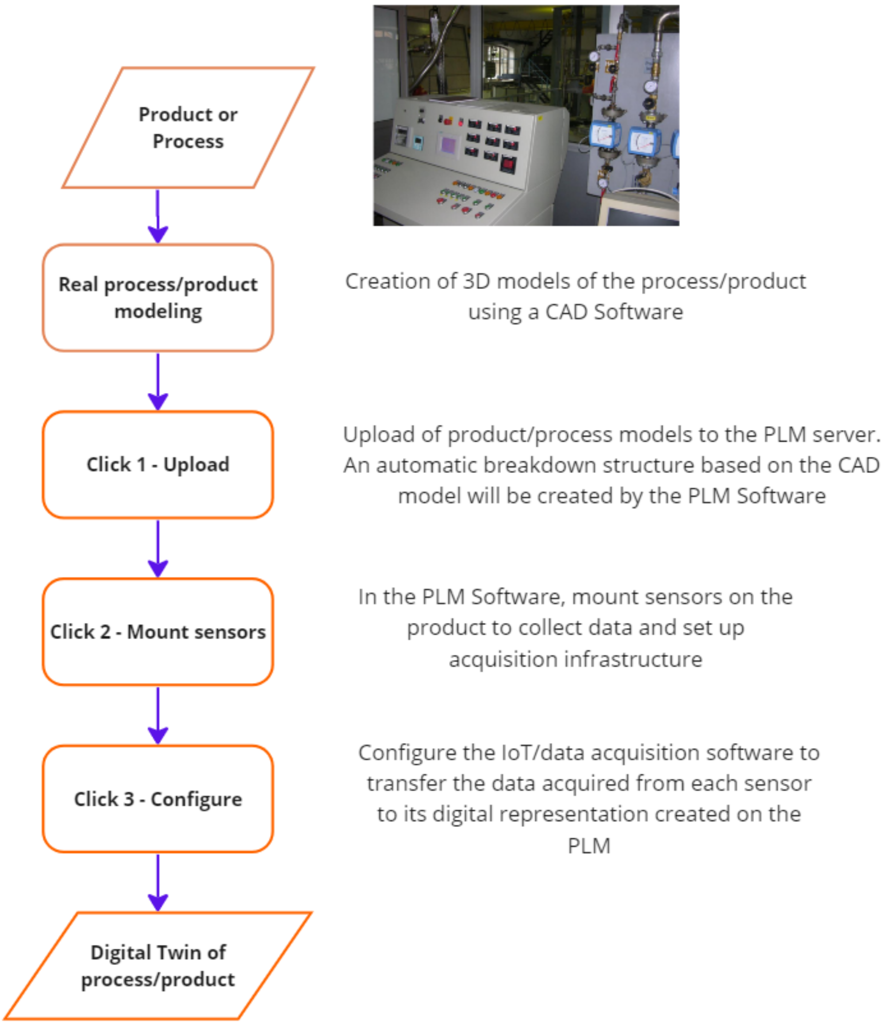

Figure 8 Example Use case flow

As the Inventory List serves as a live document and a functional tool for work within WP2 and specifically T2.6, it will be continuously updated after the delivery of D2.1. The results of the Inventory List lay the foundation for the overall system design and development and for the DT development while also enabling the exploitation of standardisation (T7.5). These results will also be fed into WP3, WP4 and WP5, where the technical integration, planning and execution of the use cases will be carried out.

2 Sustainable Underground Mining

2.1 Advanced Mobility (Autonomous and Electrified Vehicles) and Operational Excellence

The Erzgebirgische Fluss- und Schwerspatwerke GmbH (EFS) operates the Niederschlag mine and the wet-mechanical processing plant in Aue, Saxony, Germany. Currently, the Niederschlag mine is the only producing fluorspar mine in Saxony. The raw material is extracted by an underground mining operation with 42 employees. The deposit is formed as an ore vein and is mined in partial levels, which are formed by ventilation crosscuts and jig pits. Each crosscut is connected to a spiral ramp, which serves as an alignment to the vertical and as a connection between the individual working levels. The rock is loosened by drilling and blasting, and the loading and transport work is done by LHD technology. Before the raw spar can be processed wet-mechanically, it is pre-crushed underground by jaw and cone crushers and later pre-enriched by using X-ray transmission. The pre-enriched raw spar is transported to the wet-mechanical processing plant, where the production of high-quality concentrates takes place in a complex, multi-stage process by means of grinding, density sorting and flotation.

2.1.1 Detailed Overview of the Tasks and Objectives

Among the 'Pilots & Use-Cases' delineated in the initial Mine.io project proposal, falling under the category of 'Sustainable Underground Mining,' one is designated as 'Advanced Mobility (Autonomous and Electrified Vehicles) and Operational Excellence.' These particular activities are carried out by the following partners:

- Erzgebirgische Fluss- und Schwerspatwerke GmbH.
- ENXR, ACC.
- GFT, TEC, INN, HMU.
- OEM for demonstrator (in negotiation).

The above partners are developing and implementing an underground mobility solution for electric-driven battery vehicles as well as implementing autonomous driving functions in underground trucks, eliminating the issue of driver fatigue. This includes the integration of the electrification paradigm with the development of necessary charging parameters for electric-driven vehicles and the automatic docking system to the inductive loops, along with the testing of the autonomous control and navigation system as well as the demonstration of the results under real working conditions.

Depending on the selected truck provider, a conversion of underground transport from an internal combustion engine to an electric drive system may also be performed. The associated tasks and objectives are described below:

Task 1: Integration of the autonomous control and navigation systems.

- Analysis and definition of operational requirements for autonomous systems.
- Definition of obstacle and minimum and maximum detection parameters.
- Definition of obstacle classes and reaction classes.
- Creation of reaction and liberation matrix.
- Definition of communication channels between navigation and control systems and the operational control structure.

The associated user journey is expected to include the following:

- Identification of the key parameters for the integration of autonomous controls into the operational and safety systems of the underground mine.
- System developers receive information for the communication framework.
- System developers and integrators receive information for the safety framework.

Task 2: Conversion of underground transport from internal combustion engines to electric drive systems.

- Analysis and definition of the framework parameters for the introduction of electric-driven and battery-buffered systems in underground mines regarding charging infrastructure and safety.
- Parameter of influence on operational processes and requirement of change.
- Parameters of influence on safety requirements.

The associated user journey is expected to include the following:

- System developers and integrators receive information on the operational framework.
- System developers receive information on safety requests.
- Electrical engineers shall contribute to the requirements of the electrical framework.

Task 3: Development of necessary charging parameters for electric-driven vehicles

- Definition of specific requirements for the mine environment, including specific risks and electrical necessities in the mine.
- Analysis and definition of electrical necessities (charging and battery capacities as well as positioning).
- Definition of specific requirements related to the truck technology and topology, including the use case's main specific difficulties.
- Definition of the vehicle parameters within the mine geometry and the operational schemes.
- Analysis and definition of safety concept for the Dynamic Wireless Charging.
- Dynamic Wireless Charging System design for underground mining operation.
- Development and adaption of primary and secondary components.
- Development and adaption of VDSC for underground mining operation.

- Construction of first prototypes for laboratory testing.

The associated user journey is expected to include the following:

- System developers will receive the framework parameters for the inductive charging system.
- System, electromagnetic and electronic developers will adapt the current Dynamic Wireless Charging concept to the mine environment.
- Civil / Mining engineers shall contribute to the mine requirements and adaptions to the design.
- Vehicle engineers shall contribute to the truck-specific requirements and adaption to the design.

Task 4: Development of an automatic docking system for the inductive loops

- Development of an inductive loading system based on the requirements of Task 3.
- Definition and provision of the charging system for the demonstrator.
- Definition of the communication system requirements and integration into the operational control structure.

The associated user journey is expected to include the following:

- System developers and integrators will receive feedback concerning the installation and integration of the demonstrator into the mine operation.

Task 5: Demonstration of the results under real working conditions

- Risk assessment according to functional safety requirements of the whole system.
- Integration in the mine of the primary side of the Dynamic Wireless Charging track of up to 80 m, including VDSC in the mine.
- Integration of the secondary side of the Dynamic Wireless Charging into the demonstrator.
- Use of the demonstrator to show the capacity of autonomous driving and inductive charging in an underground mine.
- Integration of the necessary communication (VDSC, OBD, OSD, etc.) to the mine communication system.

The associated user journey is expected to include the following:

- System developers and integrators will receive feedback concerning the industrial verification and confirmation of the fit to operational and safety requirements.

T3.5. Workload scheduling and planning

The aim of T3.5 is to develop both a mathematical description and a functional computation prototype capable of producing optimal or close to optimal workload planning. Within the scope of this task, a methodical framework will be developed to translate the requirements and conditions gained from WP2 into a format amenable to computer implementation. This process involves identifying all constraints among the various tasks and actors participating in the planning process, as well as creating a mathematical representation to evaluate the quality of any potential solution.

T4.1 Blockchain-based traceability system for sustainable and integrated management

This task will develop a blockchain-based Chain-of-Custody together with robust databases that will be able to retain all the data generated by the project, following the trail of mining waste along the supply chain.

Chain-of-Custody:
In the context of Mine.io, "Chain-of-Custody" refers to a blockchain-based traceability system designed for the sustainable and integrated management of mining waste. This system utilises robust databases to retain all data generated by the project, thereby ensuring a transparent and verifiable trail of mining waste along the supply chain. The architecture is designed to offer secure integration with existing databases and systems utilised by relevant mining actors or organisations. The objective is to ensure traceability, accountability, and compliance with regulatory standards, thereby enhancing the integrity and sustainability of waste management practices within the mining industry.

T5.4 IIoT connection and Edge-to-Cloud connection platform

This task will implement the interconnection between the Edge and the Cloud. Edge will consist of agents responsible for collecting data from the IoT devices and other data sources on the Pilot side. The collected data will be transferred to the Cloud through an IoT gateway.

2.1.2 Used Technologies

Classification of the technologies in the mining process

Each spiral circuit within the Niederschlag mine in Saxony, Germany, has a length of 250 m to 270 m and overcomes a height difference of approx. 34 m with a total length of approx. 2,500 m at present. Mining is currently taking place on the 7th level (573 m NN). Approximately 90,000 tons of raw spar are extracted from the mine each year. As part of the research project, ENRX will equip an area of the mine (the stairway), which has yet to be specified, with induction loops to drive the electrically powered conveyor vehicles. For this purpose, ENRX is currently designing the Dynamic Wireless Charging Solution (DWCS) product. The current task consists of setting and including the mine-specific requirements in the design. Specific design requirements on robustness levels, application details (size, available space, etc.), and Electric Magnetic Field (EMF) behaviour in an underground environment need to be studied and anticipated. ENRX's plan is to design, develop and deliver a dynamic track of approx. 80-100 m that should be implemented in the ramp or the main access by the mining company with the support of a civil engineering company.

Several techniques are typically used to look for the optimal arrangement of the different processes that need to be performed within a mine. Most of the digital programs which solve for optimal planning use constraint and dynamic programming. These techniques are highly effective when the problem size remains below a certain threshold, resulting in low complexity. TECNALIA is contributing to this Task by designing new algorithms and developing a tailormade prototype, adjusted to the characteristics and constraints of the mine, capable of increasing the complexity by means of meta-heuristic evolutive methods. The prototype will use information from different databases, including the one that stores the location of the different equipment needed to complete subtasks, personnel, tasks, etc.

Blockchain-based traceability platform (TECNALIA)

TECNALIA will provide a Blockchain-based traceability platform to allow traceability of all relevant events affecting an asset throughout its lifecycle (from its creation until it is retired or disposed of). This means dealing with multidisciplinary and multi-geographical stakeholders collaborating on providing different information related to the asset. The network of stakeholders is usually very complex and several concerns about data security, integrity, or transparency can appear.

That is why Blockchain technology will be considered as it provides:

- Information integrity and non-repudiation by design, facilitating the traceability required functionality.
- High availability due to its decentralisation.
- High transparency as the same information is available for all stakeholders.
- Long-term information storage, as information recorded on the Blockchain, cannot be removed.

IIoT connection and Edge-to-Cloud connection platform (HMU)

Network communication in an underground mine is a complex procedure because of the adverse environmental conditions. HMU, along with the rest of the partners, is involved in the communication task and is responsible for enabling the network communication from IoT devices in the mine and facilitating its transfer to the Cloud through a gateway.

The implementation of the proposed Edge-to-Cloud connection will be contingent on the existing or planned network infrastructure within the mine. Currently, HMU maintains ongoing communication with Erzgebirgische Fluss- und Schwerspatwerke GmbH (EFS), leading Pilot Site 5 (Niederschlag mine) in order to gather detailed information regarding the available communication technologies and accessible network infrastructure within the mine. This investigation aims to identify suitable communication technologies for the Pilot Site 5.

The IoT gateway is a major component that will transfer the data collected from the various IoT devices and other data sources to the Cloud. As part of the search for the appropriate IoT gateway, a comprehensive market exploration is currently underway to identify a solution that fulfils all the specified requirements. According to the Description of Action, the IoT gateway should provide the following features:

- Support IoT communication protocols such as IEEE 802.11ah, Bluetooth, LoRa or other relevant standards to collect data from various IoT devices.
- Support WI-FI or any other communication protocol that guarantees reliable and consistent connectivity to the internet.
- Contain a GPU that can accommodate minor AI computations.

Autonomous driving module (ACC)

For autonomous driving, a set of cameras (visible and infrared), Lidar, radar and ultrasonic sensors will be applied to the vehicle. Modifications will also be made to the steering wheel and pedals (servo motors will be added) as well as to the main ECU of the vehicle. Advanced control systems in conjunction with custom Al algorithms will be able to analyse all the inputs of the sensors and identify paths, obstacles (static / moving) and adapt the servomotors to the wheel and pedals accordingly.

2.1.3 Functional and Non-Functional Requirements

Both the intended electrification solution with induction loops and the autonomous driving functions will be tested in real-world use after implementation and must comply with strict safety regulations. Therefore, in coordination with the project partners, the following functional have been defined:

- The autonomous vehicle can travel at a maximum speed of 15 km/h and is capable of detecting obstacles during both curved and linear driving without requiring human intervention.
- For troubleshooting, the vehicle needs to be equipped with remote control and navigation systems, which include lidar and camera information. To retrieve the data, open access to the OBD (On-Board-Diagnosis standard) of the vehicle is requested. As a non-functional requirement, the data structure of the vehicle needs to be in line with the data structure of the mining operation.
- Development and implementation of a demonstrator to show the capability and usability of autonomous driving functions under real-world conditions.
- Installation of tracks to be used for inductive charging in the mine.
- Aiming for 90% efficiency while loading with 200 kW on a 600 V battery installation of charging track on the mine site and receiver at the mine truck.

The following non-functional requirements were defined

- The WI-FI communication system designated for status control must be implemented across all sectors of the mine.
- The data structure of the vehicle needs to be in line with current data structure.

The Vehicle Detection Control Systems (VDSC) and communication systems are successfully implemented. This implies that OSD/Antenna sensors for vehicle detection are available and functional.

For the autonomous driving module own functional and non-functional requirements were defined.

Functional requirements:

Data input

The module must be able to retrieve and store data from multiple external sensors

- Retrieve data from lidar, cameras, lidar, radar and ultrasonic sensors (TBD which sensors will be used).
- Retrieve data from Retrieve data from the ECU relating the vehicle status.
- Retrieve data from the operator (start - stop commands).

Data management

The module should be able to manage information regarding the driving operation of the vehicle

- Relative to the path that the vehicle is moving.
- Relative to the distance of the vehicle from the side walls.
- Relative to the inclination of the path.
- Relative to static or moving obstacles.
- Relative to the wheel and pedal position.

Data processing

- The module must have the ability to operate with different data managed (by itself), store and manage results.
- The module must be able to manage obstacle detection.
    - With the processing of the data coming from cameras, lidar, radar, ultrasonic sensors (TBD which sensors will be used).
- The module must be able to manage driving operations.
    - With the processing of the data coming from cameras, lidar, radar, ultrasonic sensors (TBD which sensors will be used).
    - With the processing of the data coming from ECU unit.

Configuration

- The module should be able to configure parameterizable events during obstacle detection in order to avoid collision.
- The module should be able to configure parameterizable events during misaligned trajectory in order to avoid collision.

Data output

- The module must be able to send data to the ECU unit
- The module must be able to send notifications and alarms

Non-functional requirements:

Availability

- Autonomous driving module should be available from the start to the end of the vehicle trajectory

Accessibility

- Autonomous driving module should be continuously accessible from the operator.

Interoperability

- Autonomous driving module should be interoperable with the ECU unit of the vehicle.
- Autonomous driving module should has always access to 4G/ 5G or Wi-Fi networks.

Performance

- Autonomous driving module should accurately detect obstacles (no false alarms).
- Autonomous driving module should have fast response time in order to avoid collisions / accidents.

2.1.4 Further Aspects

Socio-economic factors linked to Erzgebirgische Fluss- und Schwerspatwerke GmbH (EFS) at mine in Niederschlag

Socio-economic factors play a crucial role in the implementation of sustainable underground mining practices, particularly when focusing on advanced mobility and operational excellence. The Pilot Site of Erzgebirgische Fluss- und Schwerspatwerke GmbH (EFS) and their Niederschlag mine in Aue, Saxony, Germany, provides valuable insights into the socio-economic implications of such a project. EFS operates the only producing fluorspar mine in Saxony, extracting approximately 90,000 tons of raw spar annually. In summary, the current mining operation employs 42 workers, and the site includes an underground mining operation, a wet-mechanical processing plant, and various other infrastructures.

The introduction of electric-driven vehicles in underground mining has substantial socio-economic implications. By transitioning from internal combustion engines to electric drive systems, the mining operation reduces its carbon footprint and decreases its dependency on fossil fuels. This shift towards more sustainable forms of energy promotes environmental stewardship and aligns with global efforts to mitigate climate change. Additionally, the use of electric-driven vehicles may lead to improved air quality and reduced noise pollution in the underground mining environment, benefiting the health and well-being of workers.

Moreover, developing autonomous driving functions in underground trucks presents opportunities for increased safety and productivity. Eliminating driver fatigue through autonomous control systems can significantly reduce the risk of accidents and injuries in mining operations. This not only protects the well-being of workers but also improves the efficiency of operations by minimising downtime associated with accidents or fatigue-related errors. Thus, implementing autonomous driving functions contributes to a safer and more productive working environment.

The integration of the electrification paradigm, including the development of necessary charging parameters and the automatic docking system, requires a careful consideration of socio-economic factors. It is crucial to ensure that the charging infrastructure is economically viable and feasible for the mining operation. This includes assessing the cost of implementing induction loops, designing charging tracks, and considering the maintenance and operational costs associated with the charging system. Additionally, the development of charging parameters should optimise energy efficiency and minimise costs, while providing reliable and rapid charging solutions to support uninterrupted mining activities.

EFS also emphasises in the importance of real-world testing and demonstration under actual working conditions. This demonstrates a commitment to practicality and ensures that the proposed solutions are applicable and effective in the specific underground mining context. By showcasing the capabilities and usability of autonomous driving functions, the project can instil confidence in stakeholders, both within the organisation and in the wider mining industry. This may facilitate the adoption of similar sustainable practices in other mining operations, thereby advancing the overall socio-economic transformation of the industry.

In the context of sustainability and EFS, the socio-economic factors tied to the sustainable underground mining project, focussing on advanced mobility and operational excellence, are multi-faceted. They encompass environmental considerations, worker safety and well-being, cost-effectiveness, productivity, and the potential for industry-wide impact. Integrating these factors into the project's design, development, and implementation allows EFS to optimise the socio-economic benefits of sustainable underground mining and shift more towards a sustainable and responsible mining industry.

3 DIGITALIZATION OF ASSETS AND PROCESSING EQUIPMENT

3.1 MINE.IO I4.0 ASSET DIGITALISATION

The research and education mine Reiche Zeche "Forschungs- und Lehrbergwerk Reiche Zeche" is located in Freiberg in eastern Germany, 200 km south of Berlin. Mining has a long tradition here. The first silver ore was discovered in 1168 and the mine was mostly continuously operated until 1913 as a silver mine. From 1919 to 1937, the mine was owned by the University for the first time. The second operation on non-ferrous metals was carried out from 1937 until 1969, after which the mine was handed over to the University for research and educational purposes.

The last extraction method used in this mine was narrow vein overhand cut and fill stopping. The veins contain galena, pyrite, sphalerite, and quartz. About 1100 ore veins have been mined to a depth of -750 m. Today, up to 20 veins are accessible in the mine to the 230 m Level.

At this particular Pilot Site, three partners are actively involved. First, the Technical University Bergakademie Freiberg (TU BAF) will contribute with their expertise in mining and underground communication. They will provide access to the mine and support for the partners. Second, the Luleå University of Technology (LTU) contributes with their expertise in AI analysis for measurements while drilling. The third partner is the Institute of Communication and Computer Systems (ICCS) of the National Technical University of Athens (NTUA) that provides expertise in the development of predictive maintenance technological solutions.

3.1.1 Detailed Overview of the Tasks and Objectives

At the research and education mine two different digitalisation tasks will be done during the Mine.io project. The first one deals with the installation of sensors with a data logger on an existing core drilling rig and the evaluation of the data with AI. For the second task, a digital twin of the mine ventilation shall be developed. This includes mapping and installation of multiple sensors.

Digitisation of Drill Operations

TU Freiberg has run a Sandvik DE110 core drilling machine for drilling production boreholes for another research project about in-situ bioleaching. This drill can bore drill cores up to 116 mm in diameter and 50 m in depth. It can be operated electrically. All drilling operations must be done manually. TU Freiberg only uses drill rods with 50 mm diameter and a drill bit with 55 mm outer diameter.

Currently, there are no sensors to support the operator. Consequently, the operator remains uninformed about the directional orientation of the drilling process and the extent to which the drill remains within the target rock. Additionally, the operator is tasked with manually adjusting the advance rate in accordance with the anticipated rock strength. The wear of the drill bit is also only possible by regular visual inspection.

Figure 9 Drilling Machine Sandvik DE110 (2015)

While special drill heads with measuring capability are used for large and deep boreholes, such a drill head is too expensive for a large number of simple boreholes without any special requirements, which are needed primarily for production in mining.

The objective of digitizing the drilling rig relates to simplifying the operation of the machine by displaying the operating status and AI-supported evaluation of the drilling situation. For drill bit degradation, a predictive maintenance module is developed. For this single development T5.2 is related to the Institute of Communication and Computer Systems. The AI algorithm and analysis of the measurements while drilling are included in T3.6 led by the Luleå University of Technology.

Advanced Digital Mining Maintenance

Ventilation is one of the most important infrastructures within the mining industry. Understanding the mine ventilation at Reiche Zeche can improve safety and save costs. The main task is to create a digital twin of the ventilation system. The digital twin needs to provide the following key functionalities: monitoring, simulation, optimisation, predictive maintenance, anomaly detection, failure prediction and visualisation.

The detailed steps include comparing the current ventilation model of the mine with reality. Therefore, measurements must be conducted on a continuous basis, necessitating the permanent installation of measuring equipment. For a correct ventilation measurement in mining, the integral of the ventilation velocities must be determined over the entire cross-section. Thus, a permanent, accurate measurement installation cannot be realised. However, there are various sensors that can measure air velocities across the cross-section or at a single point (several single-point measurements need to be done all over the whole cross-section to get a proper value).

For continuous monitoring, specifically calibrated mine ventilation sensors will be needed in various spots within the mine. Therefore, comparative measurements need to take place. Only afterwards a monitoring of the ventilation can be carried out. Next, it must be analysed how quick a change at the main pit fan leads to a change at the different measurement locations.

Subsequently, all the acquired data must be juxtaposed with the existing ventilation model, which closely approximates a digital twin of the mine. Due to these complex datasets, it should also be feasible to simulate new mining sections in advance.

Early planning and consideration of upcoming expansions are of particular importance for effective ventilation. It is advisable to build up a digital twin of the entire mine in order to be able to plan changes at an early stage and significantly reduce the amount of ventilation. Likewise, with good mine planning, it can be decided at an early stage which areas are to be ventilated.

3.1.2 Used Technologies

Digitisation Drill Operations

For digitisation of the drilling rig, the entire measurement technology should be located exclusively in or on the actual drilling machine. Different values should be recorded to determine the drilling success and the wear of the drill heads. While some values must be measured absolutely, such as the drilling progress, a relative measurement according to current standards is sufficient for the wear determination.

Therefore, different objectives are given. The exact sensors that will be used to measure the values on the Sandvik drilling machine are currently being selected. These details will be specified in the next Deliverable.

The objectives of digitising the drilling rig are to simplify machine operation and to enhance drilling situation evaluation through AI-supported evaluation. The operator receives a display with the current operating states of the machine. The display includes, among other things, the drilling progress, the current electrical power and the various individual outputs of the drilling rig. In the background, parallel algorithms use artificial intelligence to calculate the degree of wear of the drill bit. For this purpose, the available data on the current drilling progress, the required power, speed and the vibrations are analysed. A predictive maintenance module is used for this calculation.

The mine's vein does not have a uniform thickness and is not rectilinear. Therefore, drilling without constant adjustment of the angle will lead to drilling through the host rock. Recognising the boundaries between the vein and the side rock is of great importance for the drill rig operator. The evaluation in which material (ore vein or host rock) is drilled is to be determined with the help of artificial intelligence. A phase transition between two different rock types should lead to a substantial change in energy consumption mentioned before.

Positioning and alignment are typically done by installing various sensors behind the drill head. Data is then transmitted through the rock or cabled through the drill pipe. Both variants are not possible due to the core drilling and the resulting shape of the drill pipe. Furthermore, they are also too costly for simple production drilling. Within the project, the recognition of the rock boundary layers will be addressed as previously described.

As the drill head or bit wears, more and more energy is required to achieve the same drilling progress. However, after an initial phase with the new drill head, a plateau should form in which hardly any change can be measured. Only at the end of the service life, when the carbide tips are increasingly worn, the power consumption of the drilling machine should increase continuously in relation to the feed rate.

The drill rig at the research and education mine will also be used for demonstrating the artificial intelligence algorithms developed by LTU in task T3.6. MWD, in connection with core drilling, will be used to apply the AI algorithms developed by LTU. The following parameters are recommended for core drilling applications:

- Time (for reference).
- Length along the hole (m).
- Penetration rate (m/min).
- Feed force (N).
- Torque (Nm).
- Rotation speed (RPM).
- Flushing media flow.
- Flushing media pressure.

In Mine.io, the objectives of digitising the drilling rig relate to simplifying the operation of the machine by displaying the operating status and by AI-supported evaluation of the drilling situation and, in particular, to find the boundary layers between ore vine and side rock. The over-all planed complete technical documentation is described in Figure 10.

The Predictive Maintenance module is implemented in the form of an analytics process development tool employing machine learning, automated machine learning (AutoML), and deep learning. It processes the data generated by the installed sensors and applies advanced analytics algorithms in order to identify the actual degradation of the equipment and to predict the future health state. Therefore, it detects anomalies, predicts the wear of the drill bit, and provides recommendations about maintenance actions. To do this, it covers the whole lifecycle of data analytics, enabling the development of several independent analytics processes with different scopes (descriptive, predictive, and prescriptive) from multiple data sources and algorithms.

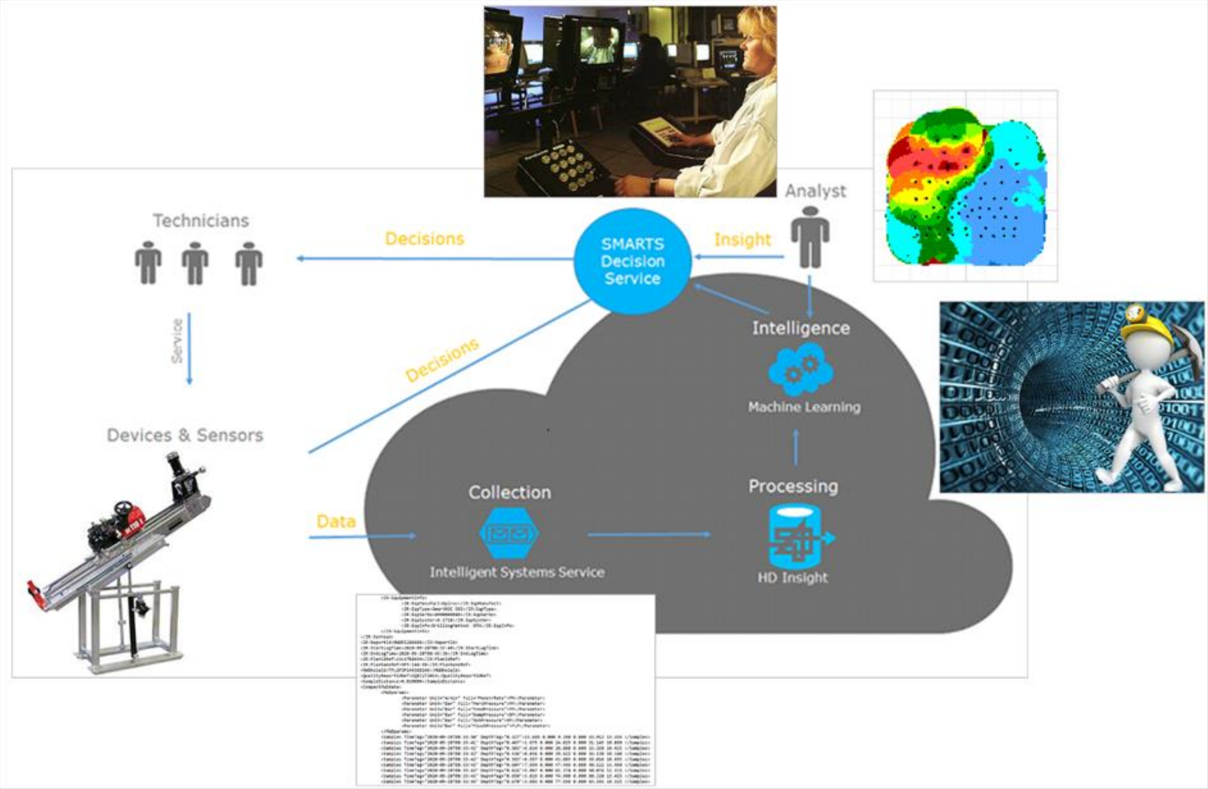

Figure 10 The complete technical documentation for data in Task-3.6

Advanced Digital Mining Maintenance

The current Mine ventilation model is a static model in Ventsim DESIGN an underground mine ventilation simulation software. A mine ventilation model can be explained as an electric circuit, where each drift is a wire with different resistance depending on the fittings and cross-section. The pressure of the ventilator can be seen as voltage and infrastructure such as doors, walls, and drapes as resistors. The main difference is the speed of the flow. While electricity travels with the speed of light, the air only flows with 0.1 m/s – 6 m/s. This means that a change in ventilation takes a lot of time to be applied in every part of the mine. Only field ventilators close to the working area can be used for quick changes within a limited range of the mine. But these are not able to increase the maximum amount of fresh air.

For the ventilation study within the research and education mine Reiche Zeche, the following sensors, measurement instruments, and software will be needed. The most important value is the airflow at the different drifts. Analogue vane anemometers – certified and in use for accurate measurements for many years – are still the most accurate measurement instruments, especially for low airflow. For digitisation and permanent monitoring, analogue sensors are not suitable.

For airflow monitoring, there are currently two options. The first option is an ultrasonic air flow meter like "Accutron PRO Series Ultrasonic Airflow Monitor" (Figure 11). This is a measurement device which measures the airflow over the whole cross-section. The other option would be a flow sensor like SCHMIDT® Flow Sensor SS 20.500 (Figure 12).

Figure 11 Accutron PRO Series Ultrasonic Airflow Monitor (Accutron Instruments, 2023)

For monitoring operations, SCHMIDT® Flow Sensor must be calibrated on a specific measurement point with the aid of comparative measurements. This measures the airflow at one point. The overall airflow can be calculated by multiple single-point measurements distributed over the whole cross-section.

Figure 12 SCHMIDT® Flow Sensor SS 20.500 (Schmidt Technology, 2023)

It is not clear at this time to what extent the integral ventilation measurement can be reduced to a single-point measurement. In the best-case scenario, it is sufficient to correlate the integral measurement results with the point measurements. In the worst-case scenario, further additional measured values must be recorded, such as air pressure, relative humidity and temperature.

In addition, due to the difficult environmental conditions underground – such as high humidity, dust and low pH levels – it is imperative to assess the durability and reliability of various measurement technologies over time.

Ventsim DESIGN will be used for developing the digital twin of the airflow model of the Reiche Zeche. Figure 13 illustrates the static model of the accessible area of the mine.

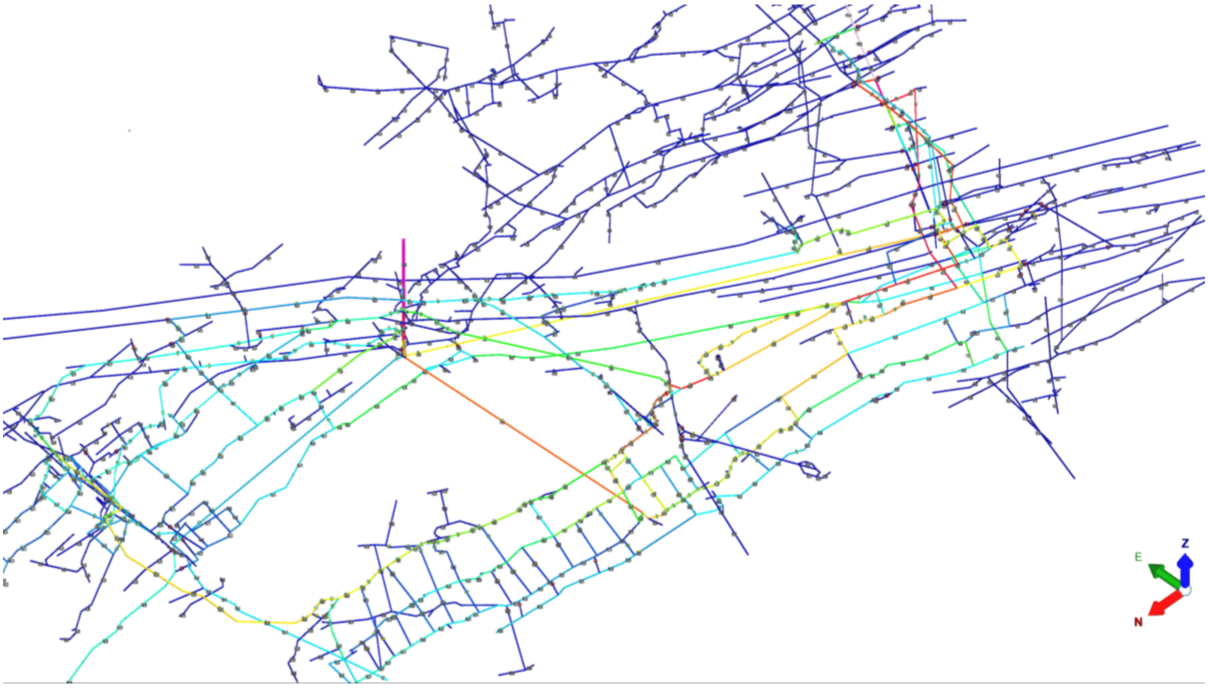

Figure 13 Ventilation model Reiche Zeche (Ventsim DESIGN)

The steady transmission of all data is of great importance for continuous monitoring. However, in mines, this is normally associated with high investments and high maintenance costs due to the continuous change in location and the multi-dimensional structure, as all drifts require complete networking. The alternative is a decentralised communication system, currently under development at the TU Bergakademie Freiberg. It uses a small box called a data collector, which can be transported through the mine, by a man or a machine, and automatically captures and uses the data from the various sensors in the vicinity. Subsequent processing only takes place when the data is forwarded to the control centre by WI-FI, which means that real-time data transmission is not possible with this system.

3.1.3 Functional and Non-Functional Requirements

Before the tasks described in the previous chapter are implemented, functional and non-functional requirements must be defined. The functional requirements for the digitisation of the drill rig are:

- Attachment of the sensors on the existing drill rig.
- Integration outside of the components.
- Sensors must not interfere with the operation of the drilling machine.

The non-functional requirements for the digitisation of the drill rig are:

- Synchronised data acquisition between sensors.
- Real-time data acquisition and storage.
- Display of current data on a control panel.

- Retrieval of data from a database.
- Data must be individualised with a time stamp.

The DT of the mine ventilation system needs to provide the following functional requirements:

- Monitoring of physical assets using sensors to capture data on environmental factors.
- Simulation-based on the digital twin models to test "what if" scenarios.
- Optimisation of the ventilation system.
- Predictive maintenance to detect early signs of equipment failures.
- Anomaly detection.
- Visualisation in dashboard and 3D model.
- Simulations with passed datasets possible.

The non-functional requirements for the digital twin are:

- Ventsim DESIGN for the design of the ventilation system is required.
- Store all measurement datasets in a database with a human-readable interface.

Requirements for measurement accuracy, measurement interval, and measurement values in both tasks will be defined by other tasks of this project depending on the algorithms. These will be added to D2.1 in the second stage.

3.1.4 Further Aspects

Environmental-socio-economic factors linked to Forschungs- und Lehrbergwerk Reiche Zeche for the digitalization of drill operations and mining maintenance

The digitalisation project at the "Forschungs- und Lehrbergwerk Reiche Zeche" in Freiberg has the potential to bring socio-economic benefits to the town and improve the efficiency and sustainability of mining operations. However, it is important to carefully assess and mitigate the potential environmental impacts associated with the project, ensuring responsible and sustainable mining practices.

The socio-economic factors linked with the projects are fourfold. The first relates to the historical significance of the mine. The "Forschungs- und Lehrbergwerk Reiche Zeche" has a long history of mining, dating back to 1168. This historical significance can attract tourists and researchers, leading to economic benefits for the town of Freiberg. In addition, the digitalization project at the mine can lead to job creation, both in terms of researchers and technicians who will be involved in implementing and maintaining the digital systems. This can have a positive impact on the local economy by providing employment opportunities for the residents of Freiberg. Furthermore, the mine at Freiberg can improve research and education since it is owned by the university and serves as a research facility. The digitalization of the mining operations can improve the research capabilities and attract more students and researchers to the town and beyond. This can contribute to the intellectual capital of the region and foster innovation and economic growth. Lastly, advanced digital mining maintenance can help reduce the cost of ventilation infrastructure. By building a DT of the mine, the planning of changes and expansions can be done more effectively, reducing the need for unnecessary ventilation, and resulting in cost savings for mining companies operating in the region.

On the other hand, the project needs to account for environmental concerns that may arise. The digitalisation of mining operations may require additional energy consumption for operating the digital systems and equipment. It is important to assess the environmental impact of increased energy consumption and explore ways to minimise it through energy-efficient technologies and renewable energy sources. Regarding air quality, mining operations can have a significant impact on air quality due to dust and emissions from mining equipment. The ventilation system plays a crucial role in mitigating air pollution in underground mines. Advanced digital mining maintenance can help optimise ventilation, ensuring proper air circulation and reducing the potential negative impact on air quality in and around the mine. Additionally, mining activities can impact water quality and availability in the surrounding areas. It is important to consider the water management aspects of the digitalization project, ensuring proper management of water resources and minimizing potential contamination of groundwater and surface water. It is also important to evaluate waste management as these operations are prone to generate significant amounts of waste, tailings, and chemical waste. The digitalisation project should consider appropriate waste management practices to minimise the environmental impact of waste generated during and after the project.

3.2 Digital Smelter – Demonstrating an Array of Digitalisation Techniques at Pilot Scale with Regard to Smelting Processes

The Top Submerged Lance (TSL) furnace at the Institute of Nonferrous Metallurgy at TU Bergakademie Freiberg, Germany, was installed in 2002 and operates according to the ISASMELT technology. The ISASMELT process from Xstrata Technology is a high-intensity smelting process that can be used in either continuous or semi-continuous operation. The ISASMELT process comprises a refractory lined furnace and a single combustion lance. The lance tip is submerged in a bath of molten slag. Air, oxygen and fuel are fed down the lance into the molten bath, where the combustion gases react with the bath/feed. All this creates a highly turbulent environment that promotes a very rapid reaction of raw materials. A scheme of such a furnace is given in Figure 14 while Figure 15 gives a view of the Pilot Site at Freiberg.

This type of smelter can be used for a wide range of applications, e.g. primary and secondary smelting of copper, lead, nickel, and converting of matte. Its ability to handle a wide range of feed materials also makes it ideal for recycling opportunities. Depending on the application, the raw materials may consist of concentrates, metal bearing residues, metal scrap, fluxes and solid fuel if required. These materials can either be fed on a continuous or semi-continuous basis through a port in the furnace roof.

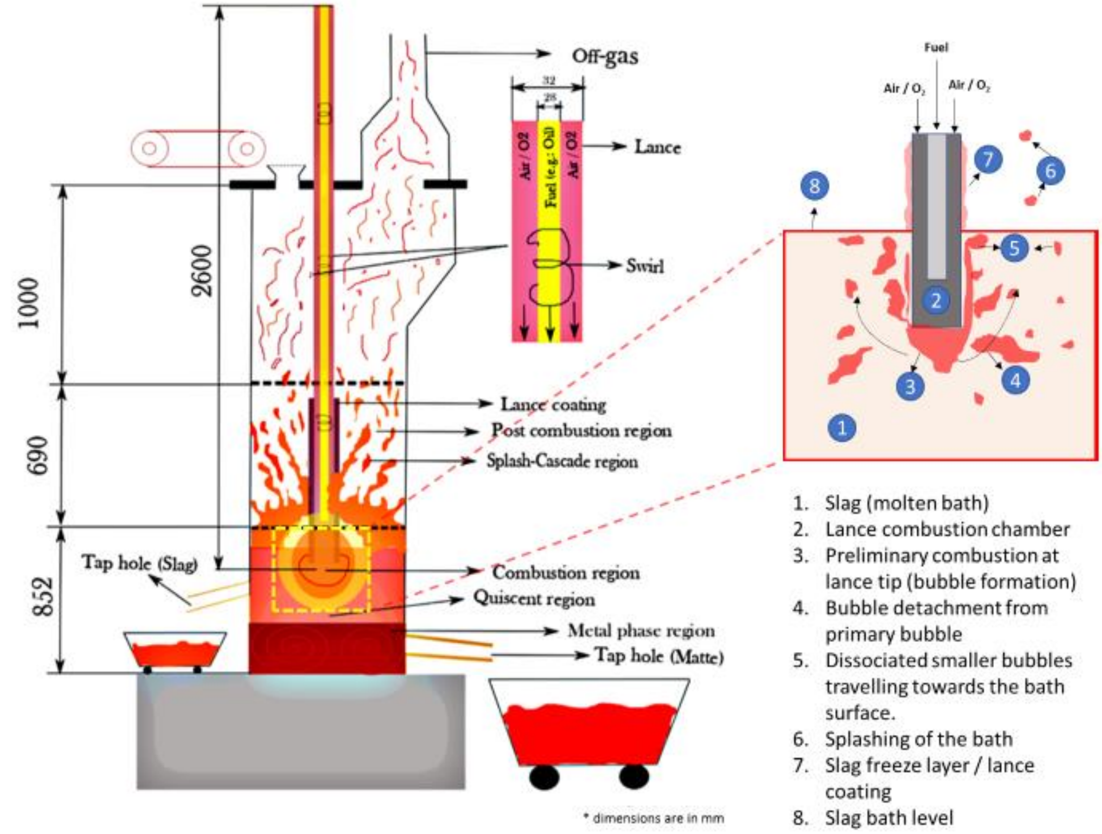

Figure 14 Schematic illustration of the TSL smelter featuring its components, mechanism and dimensions of the pilot-TSL at TU Bergakademie Freiberg

The high intensity of the smelting process results in high productivity from a relatively small diameter furnace. The raw materials only need to be mixed briefly or made into pellets on a pelletiser. Fine grinding and drying are not necessary. In secondary smelting, large lumps of raw materials can be fed into the bath. When the raw materials hit the surface of the bath, they are immediately drawn under the surface and react very quickly. This means that for any given furnace size, a comparatively large amount of raw material can be processed. Apart from its fast reaction kinetics, the ISASMELT TSL furnace is fuel flexible and the SO_2 and dust emissions from the TSL furnace are lower than the traditional smelters, making it a safe operation for a clean environment. (Xstrata Technology, 2001)

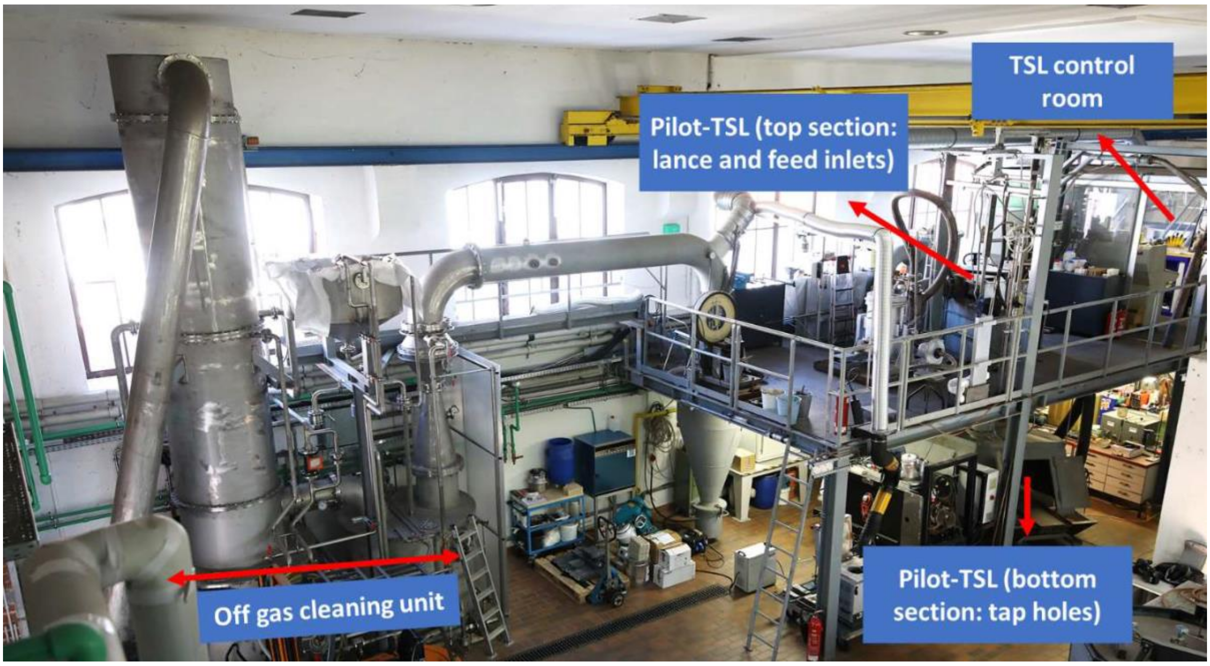

Figure 15 Photo of the TSL Smelter with the off-gas cleaning unit in the furnace hall of the Institute of Nonferrous Metallurgy at TU Bergakademie Freiberg

3.2.1 Detailed Overview of the Tasks and Objectives

The Mine.io project aims to demonstrate the application of an array of sensor techniques, combined with simplified embedded models derived from Computational Fluid Dynamics (CFD) calculations and online process models (digital twins), to optimise smelting operations, leading to next-generation advisory operator systems, or even to fully digitised solutions demanding minimal human intervention using the example of a Top Submerged Lance (TSL) smelter that is equipped with dedusting and wet gas cleaning sections.

It is typical in metallurgical plants that analysis, e.g., of molten phases, take several hours to complete, while respective probes need to undergo tedious preparation. This is the case, when using offline X-ray fluorescence (XRF) to determine slag composition. Furthermore, the fluid dynamic state of the furnace, which is pivotal for the distribution of pay metals among the various phases, is not directly measured. Similarly, the partial pressure of oxygen, a critical factor for element distribution, is deduced through offline process models.

Digitisation in smelting and metallurgical processing will only be successful if advanced sensors are coupled to online process models (digital twins). The latter need to be predictive and act as triggers to advanced control loops. Ground-breaking sensor technologies, such as acoustic measurements to predict bath smelting fluid dynamics, Frequency-Modulated Continuous Wave (FMCW) radar technology to understand molten phase properties, and Laser-Induced Breakdown Spectroscopy (LIBS), combined with temperature, partial pressure of oxygen in molten phases and gas composition measurements enable advanced online monitoring. Together with the digital ACT platform from Metso Outotec (ACT stands for

'Advanced Control Technology') and the HSC-Sim simulation software, these sensors can be integrated into reactive models. Hence, the creation of a truly sensor-based digital twin is a reliable way to digitise smelting processes as a family based on the principle "measure-predict impact-act".

Therefore, this pilot use case aims to combine the existing infrastructure with novel sensors to create a digital twin that makes it possible to monitor the metallurgical processes, predict their progress and control them as precisely as possible. Finally, this is intended to lead to optimal removal of impurities and recovery of valuable metals.

In detail, this means the following tasks:

- The integration of the existing infrastructure into the plant's ACT platform encompasses multiple key components. These include temperature measurement via thermocouples, flow rate and pressure measurement for various fluids such as fuel oil, compressed air, and oxygen, as well as cooling water in the off-gas cleaning system. Additionally, the position measurement of the lance is incorporated into the platform.
- Using Fourier Transform Infrared Spectrometry (FTIR) to measure off-gas composition.
- Understand smelting fluid dynamics through acoustic measurements:
    - Determination of bubble dynamics that change acoustic frequencies (influenced by bath and lance properties).
    - Identification of the change in the bath properties (i.e., viscosity, density, and surface tension) and lance properties (i.e., combustion, dimension, and lance submersion depth) to evaluate the process flow.
- Assess the properties of the molten phases (slag and metal phase), including thickness, density inhomogeneity, and distribution through FMCW technology.
- Measure slag composition through online molten phase LIBS in real-time.
- Direct measurement of the oxygen partial pressure to determine Lambda-value in real-time.
- Test different pyrometer solutions for reliable molten phase temperature assessment.
- Incorporation of the advanced sensor measurements into the ACT platform and implementation of online process models (use of HSC-Sim software) to predict the smelting process through simplified modelling equations derived from the Computational Fluid-Dynamics models.

3.2.2 Used Technologies

The requirement and possibility of recording the above-mentioned process data are to be demonstrated here using the example of a process for copper scrap recycling. When recycling copper scrap using TSL technology, different types of scrap are used simultaneously as feed material. These consist of metallic copper and copper-containing alloys as well as metal/plastic compounds and oxidic residues. In addition, slag-forming additives (e.g., SiO_2) are used. While the plastic fractions in this process act as fuel, all other fractions are reprocessed. For example, iron in the raw material is slagged, zinc is removed in the form of ZnO as flue dust and can later be reprocessed as Waelz oxide. Nickel, tin and lead are first converted into the metal state together with the copper and later slagged as oxides in order to reprocess them independently of the copper.

Initially, all materials are melted in the TSL furnace, in which a slag bath is already present, by energy input via the lance. Copper oxide is already partially metallothermically reduced here, and an oxidic fayalite slag (Fe_2SiO_4) and metal oxides are formed. The metal oxides, such as ZnO, can be gaseous and discharged via the off-gas.

$Cu_2O + (Zn,Fe,Sn,Ni,Pb) \longrightarrow 2Cu + ZnO(g)+FeO+(Sn,Ni,Pb)O$
$2FeO + SiO_2 \longrightarrow Fe_2SiO_4$

After melting, the process is carried out under reducing conditions ($\lambda < 1$). In this case, the process uses the exhaust gas (e.g. CO) produced by the combustion of the fuel to reduce the oxides of the valuable metals, i.e. to convert them into the metallic state. CO_2 is formed in the process, which is purged via the off-gas. The valuable metals (i.e., Sn, Pb or Ni) collect in the copper melt, while the fayalite slag is discharged at the end of this process stage.

$Cu_2O + CO \longrightarrow 2Cu + CO_2$

In the following process, work is now carried out under oxidising conditions. For this reason, the air blown in via the lance must be enriched with oxygen to achieve a lambda value above one ($\lambda > 1$). The copper remaining in the furnace is now converted. The oxygen is dissolved in the melt, and impurity elements are removed from the copper melt by means of selective oxidation and slagged as oxides. At the end of this process, some of the metallic copper oxidises as well. The end products are crude copper, which is further refined in the anode furnace, and a copper-rich slag for Pb/Sn recovery in the electric furnace.

$O_2 \leftrightarrow 2O_{Cu}$
$O_{Cu} + (Sn,Pb,Ni,Zn)_{Cu} \leftrightarrow (Sn,Pb,Ni)O + ZnO(g)$
$2Cu + O_{Cu} \leftrightarrow Cu_2O$

In order to be able to control this entire process, it is absolutely necessary to set the lambda value in the furnace correctly. Until now, this has been done manually by controlling the flow rates of fuel oil, compressed air and oxygen while simultaneously measuring the temperature at the inlet and the exhaust gas and discontinuously determining the composition of the off-gas. The oxygen partial pressure in the furnace can be calculated from these data. The position of the lance can be changed mechanically to keep the heating zone within the desired, previously calculated range. Sudden temperature changes, e.g. due to exothermic processes, can be detected. Furthermore, an assessment of the course of the process can only be obtained by means of sample taking (tapping) and subsequent separate XRF analysis of the product. Therefore, the direct measurement of the oxygen partial pressure by means of a sensor, the continuous measurement of the off-gas composition, identification of changes in fluid dynamics (e.g. viscosity and density), and the determination of the slag composition in real-time using LIBS would be more elegant and help to improve the whole process monitoring. The latter, could be used to precisely determine the end of the process and thus prevent overoxidation of the copper because selective oxidation is complete when the metallic copper starts to oxidise. Before tapping, i.e. at the end of each of the two process stages, it is important to obtain a good separation between the two phases, slag and metal. This is generally achieved by a certain settling time. The planned radar measurements help to determine the point of optimal phase separation so that too high losses of valuable metals in the slag are avoided. Figure 16 shows a typical fayalitic slag generated during the primary metallurgical copper production. The diversity of phases is readily apparent in this representation. Moreover, the slag contains not only non-metallic phases but also includes some metallic inclusions, thereby adding to its compositional complexity.

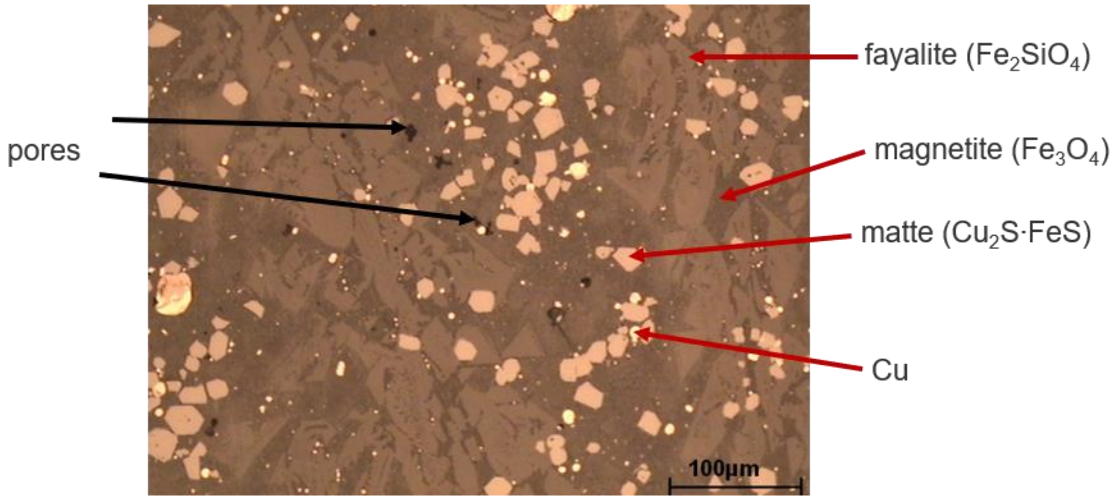

Figure 16 Typical composition of a fayalitic slag from the primary copper process

Additionally, acoustic signals and motion sensors are to be coupled to provide overall bath properties such as viscosity and density. For example, if there are many acoustic frequency peaks, then the bath is low viscous. On the other hand, if there are fewer peaks, then the bath is higher in viscosity. Similarly, a viscous bath provides less movement on the motion sensor data. The above thresholds for individual measurements shall be coded on the ACT software. For example, when the viscosity increases, the model can raise the temperature of the bath by adding fuel/air or adding certain additives.

The goal of the digitalisation of the TSL smelter is to demonstrate a beyond state-of-the-art sensor-based digitisation technology for smelting at TRL6 level, using a pilot plant unit. In the end, the aim is to develop an advanced DT system (by utilizing the plant ACT platform) incorporating advanced measurements, online process models (use of HSC-Sim software), and simplified modelling equations derived from CFD models. Furthermore, advanced sensors to the digital twin platform, including acoustic measurements (to assess bath fluid dynamics), radar and LIBS measurements (to assess slag properties), off-gas measurements (through FTIR methodology), temperature, and bath partial pressure of oxygen shall be incorporated with the aim of optimally removing impurity and valuable metal recovery.

3.2.3 Functional and Non-Functional Requirements

The ACT digitalisation platform is a commercial product of Metso Outotec and is equipped with the commercial software HSC-Sim, which can be used for online DT simulation. Both require a Windows operating system. Simplified TSL lance Computation Fluid-Dynamics models will be adjusted to HSC-Sim and the ACT platform to aid accuracy. Flowsheet models like Metso Outotec's ACT platform can predict thermodynamic data when relevant input data is provided. The more data is entered into the software, the more accurate the output. For example, the ACT platform can be modelled dynamically. This means that the software can adapt the real-time data and predict outcomes such as thermodynamics, off-gas composition, lance life, refractory wear, productivity/metal yield, emissions, etc. With the help of these predictions, the ongoing metallurgical process can then be controlled in a specific way.

To achieve all this, the installed sensors must provide reliable data within the set tolerances. As these data are to be generated online during the metallurgical processes, the response time of the sensors should be within seconds. The corresponding analysis results must be available within minutes. Should a failure of the sensors occur, it must be ensured that the running process can be shut down, at least in a controlled manner. For this purpose, absolutely necessary sensors, such as temperature sensors, must be redundant, while others, such as gas flow meters, must remain manually controllable. Other sensors should be able to be replaced in a reasonable time period to minimise downtime. In addition, it would be desirable if new sensor technology could be integrated into the existing system.

3.2.4 Further Aspects

Environmental-socio-economic factors linked to TU Bergakademie Freiberg for Digital Smelter

The implementation of digitalisation techniques in smelting processes at the Pilot Site at Freiberg has the potential to have significant environmental and socio-economic benefits. The optimised smelting operations can lead to reduced emissions and resource consumption while also improving productivity, safety, and competitiveness in the industry. The integration of advanced sensor technologies can also drive innovation and stimulate further advancements in the sensor technology sector.

The application of digitalisation techniques in the Freiberg Pilot Site for smelting processes can have several positive environmental impacts. The ISASMELT TSL furnace, which is already in operation at the test site, is known for its fuel flexibility and low SO_2 and dust emissions compared to traditional smelters. The digitalisation project aims to further optimise smelting operations and reduce emissions by integrating advanced sensor technologies and online process models. One of the key environmental benefits of the project is the ability to monitor and control the smelting process more precisely, leading to improved removal of impurities and recovery of valuable metals. By accurately measuring and predicting the metallurgical processes, unnecessary waste and emissions can be minimised. For example, the direct measurement of the oxygen partial pressure in the furnace can help control the process conditions, preventing overoxidation of copper and reducing the generation of CO_2 emissions.

The project also aims to optimise the separation of slag and metal phases, which can contribute to reducing the loss of valuable metals in the slag. By identifying the optimal point of phase separation using radar measurements, the number of valuable metals trapped in the slag can be minimised. This not only enhances the efficiency of the smelting process but also reduces the environmental impact by maximizing the recovery of valuable resources.

Furthermore, the DT system, integrated into the ACT platform, allows for real-time monitoring and control of the smelting process. By continuously analysing and adjusting the process parameters, such as temperature, fuel/air ratio, and additives, the system can optimise the efficiency of the process and minimise energy consumption. This results in reduced greenhouse gas emissions and overall resource consumption. The digitalisation techniques in smelting processes have several potential socio-economic benefits. The project aims to demonstrate the application of advanced sensors combined with online process models to optimise smelting operations, leading to next-generation advisory operator systems and even fully digitised solutions that require minimal human intervention. Primarily, one of the main socio-economic benefits is the improved efficiency and productivity of the smelting process. The high-intensity smelting process of the ISASMELT TSL furnace allows for high productivity from a relatively small diameter furnace. By further optimizing the process through the integration of advanced sensor technologies and online process models, the project aims to increase productivity, reduce downtime, and improve the overall competitiveness of the smelting industry. This can have a positive impact on job creation and economic growth. Additionally, the digitalisation of smelting processes can enhance the safety of the operation. By accurately measuring and monitoring the process parameters, potential hazards can be detected and mitigated in real time. For example, sudden temperature changes can be detected, and appropriate actions can be taken to prevent accidents or equipment failures. This creates a safer working environment for operators and reduces the risk of workplace accidents.

Moreover, demonstrating the integration of new sensor technologies into the existing infrastructure is vital. This improves the efficiency and accuracy of the smelting process and drives innovation and development in the sensor technology industry. Showcasing the successful integration of new sensors allows the project to stimulate further advancements and investment in sensor technologies, benefiting not only the smelting industry but also various other sectors that rely on sensor technologies for process optimization and control.

3.3 Digital Flotation System – Artificial Intelligence Technology for Monitoring and Control of Metal Ore Processing

This Pilot Site is located in Polkowice, Poland, in the KGHM Mineral Processing Plant. KGHM is the biggest Polish company with a big international component, involved in mining, mineral processing and smelter activities.

The copper ore is mined in the KGHM mines in the Lubin area. Subsequently, the ore goes through the enrichment process in the KGHM Concentrator Plants. The most important technological process in this place is the flotation process. The Photonic-IT (PIT) System will be installed and tested on one of the flotation cells in this plant.

The contributors involved are KGHM, Ł-ITR, Ł-EMAG, AGH, and LTU. The expected main impacts can be summarised as follows:

- KGHM will make accessible the flotation technological line for the PIT System installation and tests. It will also adapt the flotation technological process for the PIT System requirements and Pilot process demonstration.
- Ł-ITR, which will develop the PIT System and, together with KGHM, will install it on the flotation cell.
- Ł-ITR and Ł-EMAG will develop and perform the Machine Learning (ML) and Artificial Intelligence (AI) processes that will give algorithms for the flotation froth content monitoring.
- AGH and LTU will give the technological support for understanding the flotation process.

3.3.1 Detailed Overview of the Tasks and Objectives

The main tasks which will lead to the Pilot process are contained in the WP4 and WP6 and can be summarised as follows:

- T4.3: Artificial Intelligence technology for monitoring, control of metal ore processing.
- T6.3: Pilot Side 2: Poland.

They were divided into the following subtasks:

Subtask 1 Development of the Photonic-IT System installation plan on ZWR industrial machines.

The scope of this subtask is:

- Development of detailed assumptions for the Photonic-IT (PIT) System.
- Design and selection of system components.
- Development of the PIT System architecture and selection of its implementation technology.
- Development of the analytical engine responsible for the implementation of analytical tasks.
- Development of the structure of the repository for measured data.
- Development of a methodology for data exchange between individual PIT System modules.
- Determination of test points and verification of the proposed solution in terms of application in O/ZWR.

Subtask 2 Development of a methodology for the flotation process control for generation of flotation froth with various metal contents in the froth during registration of the training groups of images.

The scope of this subtask is:

- Development of a theoretical description of process control (assumptions + implementation plan = verified concept).
- Identification of the key parameters affecting the results of the process.
- Determination of the industrial conditions for various flows of the flotation process.
- Development of the methodology for experiments enabling the collection of froth images for various process conditions and enrichment results.
- Development of the methodology for conducting the flotation process to obtain the flotation froth of various Cu content, determination of the measurement points and the methodology of froth sampling for Cu content identification. Determination of the possibility of obtaining a technological balance and technological indicators based on the Cu content measurements in a flotation froth. Analysis of the washed concentrate samples in terms of mineralogical, lithological and grain composition corresponding to the relevant images of the flotation froth.
- Selection of a flotation machine for the PIT System installation.

Subtask 3 Development of analytical algorithms and image processing software for machine learning (ML) and artificial intelligence (AI) processes.

The scope of this subtask is:

- Development of the technical side of the PIT System - hardware and software.
- Installation of the test PIT System on one selected flotation machine.
- Performing the preliminary tests: initial registration of the groups of training images in the O/ZWR on one selected flotation column, froth samples collections, measurements of the flotation froth content by XRF and chemical methods.
- Verification of stability of metal content in flotation froth, evaluation of estimation errors and determination of factors influencing the measurement process accuracy for estimation of the Cu content in a froth. Comparison of the results obtained from the PIT System, chemical analyses and XRF measurements.
- Development of image processing, data cleaning and transformation methods, construction of the sets of parameters describing the images and determination of the appropriate representation of the acquired images in order to create training and test sets used by machine learning algorithms.

Subtask 4 Development of machine learning algorithms and software combining the parameters of flotation froth with the content of monitored metals in the froth.

The scope of this subtask is:

- Use of analytical results from subtask 2 for technological verification of the description of the process control.
- Test of Machine Learning algorithms: Discriminant analysis and Neural networks.
- Selection of machine learning algorithms to generate models of the best quality.
- Application of the ML and eXplainable Artificial Intelligence (XAI) algorithms for verification of the correctness of the created models.
- Analysis and verification of applied ML and AI technologies.

Subtask 5 Tests of the optical system in industrial conditions of flotation, registration of training groups of images for various contents, verification against chemical analyses of flotation froth (in terms of content), analysis of results in terms of efficiency of the flotation process.

The scope of this subtask is:

- Installation of the PIT System in the O/ZWR on the selected flotation machine.
- Preliminary tests, integration and verification of the technology developed under Tasks 3 and 4 in the industrial conditions.
- Tests of main software algorithms and procedures for ML process: registration of groups of training images on test stands, collection of the flotation froth samples, froth samples analysis by the XRF chemical methods, Artificial Neural Network and Discriminant Analysis data processing.
- Development and verification of technological algorithms described in Task 2.

Realisation of the above subtasks will allow us to obtain the following Objectives:

- Applying a PIT in the copper ore flotation process for online determination of the copper content in the flotation froth and delivering this information to the flotation control systems.
- Development and verification of the ML and AI algorithms for automating and optimisation of the flotation process control based on the online information about the froth content.
- Determination of technological and economic potential of the PIT in industrial conditions of the copper ore processing plant.

3.3.2 Used Technologies

The most important technology for ore processing is the flotation technology. Consequently, it was selected for digitalisation within the Mine.io project. For this process, the photonic, optic, electronic and IT technologies will be applied in the PIT System, where ML and AI algorithms will be applied to monitor the Cu content in the flotation froth.

Ł-ITR will develop the PIT System and Ł-EMAG will construct the ML and AI algorithms and then apply them to the software. AGH will give technological support for understanding the flotation process. KGHM will make accessible the flotation technological line for the PIT System installation and tests. It will also adapt the flotation technological process for the PIT System requirements and Pilot process demonstration.

The flotation process at Pilot Site 2 will also be used for demonstrating the service of Online optimisation of primary and secondary production, developed by LTU in T4.5. This service will be based on advanced control concepts for real-time optimization, such as Model predictive control and extremum-seeking control.

3.3.3 Functional and Non-Functional Requirements

Functional requirements from the Pilot Site to the Technology Partner include:

- PIT system will perform the flotation froth image acquisition.
- PIT system will store the collected images in the high-capacity memory.
- PIT system will make possible the Image-based prediction of metal content in flotation froth.
- PIT system will make possible the assessment of the metal content in the flotation froth samples.
- PIT system will clearly present the results.

Non-functional requirements from the Pilot Site:

- The flotation froth images and the flotation process data should be of proper quality.
- The capacity of the database is sufficient.
- A graphical user interface exists at the PIT system.

Requirements from the Technology Partner to the Pilot Site include:

- KGHM will make accessible the technological flotation line for the experiments and installation of the PIT System.

3.3.4 Further Aspects

Environmental-socio-economic factors associated with the KGHM Mineral Processing Pilot Site

KGHM is looking to adapt the flotation process to meet the requirements of the PIT System, in addition to supporting and assisting in the installation and testing of the aforementioned system. Their tasks also involve sampling flotation froth for analysis and verification and data gathering with feedback on the performance of the PIT System. The installation and use of the PIT System in the KGHM Mineral Processing Plant exudes several environmental impacts. The use of photonic, optic, electronic, and IT technologies in the PIT System requires materials and resources that have environmental implications, such as producing electronic components and using energy for operation. Additionally, the installation and operation of the PIT System involves modifications to the existing flotation process, which could have environmental consequences.

Furthermore, the use of ML and AI algorithms in the PIT System necessitates additional computational resources and energy. The increased use of computational resources and energy could have indirect environmental impacts, such as increased carbon emissions or energy consumption. Hence, it is important to consider and minimise these environmental impacts by implementing measures to reduce resource consumption, optimise energy use, and minimise the use and impact of chemicals and materials. However, such impact is negligible compared to the positives of the application of the new technology.

Mine.io project will have several positive socio-economic impacts on the Pilot Site in Polkowice, Poland. The installation and use of the PIT System in the KGHM Mineral Processing Plant will require collaboration and cooperation between various stakeholders, including KGHM, Ł-ITR, Ł-EMAG, AGH, and LTU. This collaboration creates opportunities for knowledge exchange, technology transfer, and capacity building among the project contributors. The implementation of the PIT System will also result in improvements in the flotation process control and optimization. With real-time information on the metal content in the flotation froth, the PIT System will provide an effective control strategy, leading the beneficiation process to a state of optimal performance by the control and optimisation, through advanced computer vision and appropriate control of the froth flotation process. It will allow for more efficient and effective ore processing, which can lead to cost savings and increased productivity for KGHM. It will reduce the analysis time of copper ore content, increase operational recovery in the rough flotation, reduce the electrical energy consumption for chemical and X-ray analyses of metal content in the froth as well as reduce the X-ray emission and reduce the consumption of flotation chemicals.

Moreover, the Mine.io project has the potential to create economic benefits through the development and commercialization of the PIT System and the associated machine learning and artificial intelligence algorithms. This technology can be applied not only in the mining industry but also in other industries that rely on the flotation process for ore processing.

Therefore, the potential contribution of the overall project to the economic development and sustainability of the KGHM Pilot Site and the wider region by improving the efficiency and effectiveness of metal ore processing, creating knowledge and technology transfer opportunities, and generating economic benefits through the development and commercialisation of the PIT System.

4 Digital Solutions for In-Situ Mining Exploration

4.1 In-Situ Underwater Exploration Technology Validation for Water-Filled Mines

Pilot Site 6 consists of two sites, one located in the northwest of Portugal at the Malaposta open pit. The second site is the Urgeiriça mine located near Viseu in central Portugal.

The Malaposta Open Pit is an active gneissic quarry for aggregate and armour stone. It is owned by IRMAOSCAVACO S.A. located in Santa Maria da Feira. At this site, gneiss of different densities and compositions are currently being mined. These are:

- Biotitic orthogneiss, coarse to medium grain, low to medium weathering grades.
- Biotitic gneiss, quartz and large feldspar mega crystals, strong shear fabric and high density.
- Porphyroblastic garnet biotite, highly tectonised.

At the open pit, there are currently flooded areas that are not subject to active mining. The flooded pits are about 80 m deep and there is access to the water through ramps. Furthermore, there is access to local storage facilities, an electric power generator, 4G telecommunications and a partial aerial LiDAR scan of the environment. For these reasons, the pit site is used as an ideal test- and demo site for both the muon imaging technology (based on a so-called muon telescope) and the deployment of autonomous underwater robots.

The second test site of Pilot Site 6 is the abandoned Urgeiriça mine in central Portugal. Opened in 1913, it was a mining site for both radium and uranium until 1991, when it seized operation. Over time, both cut-and-fill mining and in-situ leaching were used as mining techniques. Through six vertical shafts, an underground space of around 1 km in length and 500 m in depth is accessible. However, today, the entire mine is flooded. At the Santa Bárbara shaft, the water level is at around 8 m depth. All 18 galleries are accessible from this shaft through a hatch. At the shaft, there is a control room, access to fibre optic communications equipment to the shaft, power and internet connectivity and a winch for deployment of heavy equipment. At this time, the facility is used as a test site of INESC TEC for their AUV robot, which is exploring the mine and 3D mapping it.

The contributors and Technology Partners of this Pilot Site are:

- INESC TEC.
- Muon Solutions Oy.
- Wigner Fizikai Kutatokozpont.
- UNEXMIN Georobotics Ltd.

4.1.1 Detailed Overview of the Tasks and Objectives

The main tasks which will lead to the pilot process are contained in the WP3 and WP6 and can be summarised as follows:

- T3.1: Muon imaging and monitoring instrumentation for mining applications and for in-situ underwater exploration.
- T3.2: Underwater vehicle for in situ exploration in flooded mines and UAV-derived 3D imaging.
- T6.7: Pilot Side 6: Portugal.

As said, Pilot Site 6 includes two different sites. More precisely, the following subtasks are divided into the Malaposta open pit and the Urgeiriça Mine.

Tasks for Malaposta open pit:

Subtask 1 Development of an underwater muon telescope system prototype, with the following steps:

- Application requirements analysis and definition.
- Design and selection of system components.
- Design and develop the pressure-resistant housing for the muon telescope.
- Design the energy subsystem for long-period powering of the muon telescope.
- Design and development of the muon telescope electronics for low-power long-lasting operation.
- Integration of the muon telescope.
- Underwater validation of the muon telescope.
- Define the interface for mounting the sensor, define the communication interface between the robot, the sensor and the control room, and test the robot and muon telescope.

Subtask 2 Development of underwater muon imaging system prototype, with the following steps:

- Development of the processing software.
- Validation in an underwater environment.

Subtask 3 Design and development of system and methods for the muon system prototype deployment, with the following steps:

- Study the typical muon survey needs for deployment and define the strategies and methods for the muon telescope deployment.
- Design and develop a mechanical interface between the muon telescope and the underwater transportation vehicle EVA AUV.
- Adapt the underwater vehicle EVA AUV for transporting and precisely deploying muon telescopes and for their recovery later.
- Design and develop the mission specification tools for the deployment/recovery operations.
- Design and develop the launch and recovery system to deploy the EVA AUV with muon telescope attached.

Subtask 4 Full validation of the operation of the underwater muon imaging in a water-filled field basin, with the following steps:

- Design the validation plans for the integrated underwater muon imaging system.
- Test and validation of the deployment tool for accurate deployment of the muon telescopes.
- Test and validate the muon imaging process software with the data gathered.
- Test and validate that the output data can be exported to the mine digitalisation system.

Tasks for Urgeiriça Mine:

Subtask 1 Design and development of wireless operation methods for the Autonomous exploration underwater robot, with the following steps:

- Analysis and definition of requirements for wireless operation of the autonomous exploration underwater robot (UX1neo).
- Design and development of a short-range wireless communication system, considering optical and acoustic options.
- Integration of an optical/acoustic modem in UX1neo and deployment system.
- Design and development of new operation modes for wireless connected operation.
- Implementation and testing of the wireless communication system in a controlled environment (lab).

Subtask 2 Development of Autonomous Exploration Software for the robot, with the following steps:

- Identification of requirements for onboard autonomous navigation and exploration software.
- Identification of the most useful new autonomous exploration manoeuvres for the UX1neo system.
- Design and development of those additional autonomous exploration manoeuvres.
- Integration and testing of autonomous exploration software with the robotic system in a controlled environment.

Subtask 3 Design and Development of Underwater Data Export System for the integration with Mine.io system, with the following steps:

- Analysis of requirements of the UX1neo survey data types and of the converting and exporting software.
- Development of software to process and export data collected by the UX1neo robot.
- Testing and validation that the exported data can be integrated into the Mine.io system in a controlled environment.

Subtask 4 Full validation of the operation of the autonomous exploration underwater robot in the flooded underground mine, with the following steps:

- Design the validation plans for the autonomous robotic system.

- Testing and validation of wireless operation.
- Testing and validation of the developed autonomous exploration manoeuvres.
- Testing and validation of the underwater data export system.
- Refinement of system functionalities based on the results of the field trials.

4.1.2 Used Technologies

This Pilot Site uses two different technologies at the sites. The Wigner Research Centre of Physics and Muon Solutions Oy are developing a prototype muon telescope for flooded environments. The telescope will be used as an underwater muon imaging system. Muon monitoring is based on the detection of cosmic-ray muon radiation to provide information about the density variations of rock formations, material heaps or cavities in large-scale solid-state structures. By detecting the absorption of muons as a function of density, it is possible to make individual measurements or even tomographic imaging of up to 1 km thick layers of rock or any material. (Muon Solutions, 2023). For the accurate positioning of the muon telescope underwater, an AUV (the INESC TEC EVA AUV) will also be adapted as it can transport, deploy and retrieve the underwater muon telescope.

Unexmin GeoRobotics, together with INESC TEC, are developing and testing the autonomous exploration underwater robot. The Autonomous Underwater Vehicle (AUV) UX1-Neo will be further developed for autonomous on-board navigation and exploration, adding underwater communications systems (optical or acoustical) to achieve a tetherless operation.

4.1.3 Functional and Non-Functional Requirements

The main functional and non-functional requirements for Pilot Site 6 are presented below for each mining/metallurgical phase:

Functional requirements include:

- Have an underwater muon telescope prototype capable of long-term deployments underwater at shallow depths.
- Have an underwater muon imaging system prototype with high resolution for geological exploration.
- Have a muon telescope deployment tool capable of accurately positioning it underwater.
- Have a wireless autonomous exploration underwater robot capable of operation in a 30 to 50m range from the deployment system.
- Test and validate the new autonomous operation of the autonomous exploration underwater robot.
- Have data export system for the underwater surveys compatible with Mine.io system.

Non-functional requirements include:

- To characterise the underwater muon telescope prototype, i.e.:
    - Systems dimensions compatible with transporter AUV capabilities less than 40x40x40cm.

    - Have biofouling-resistant protection.
    - Have a design that allows access to electronics parts for maintenance.
- To test and validate the underwater muon imaging system.
    - Several deployments in different positions are required for the muon tomography process.
- Launch and recover system to deploy the EVA AUV with an attached muon telescope.
- Reliability and robustness of the attach/detach tool.
- Reliability and robustness of the wireless exploration.
- Reliability and robustness of the developed autonomous exploration manoeuvres.
- Follow Mine.io data standards.

4.1.4 Further Aspects

Environmental-socio-economic factors at the Malaposta open pit and the Urgeiriça mine

The Mine.io Pilot Site in Portugal consists of two sites: the Malaposta Open Pit located in the northwest of Portugal and the Urgeiriça mine near Viseu in central Portugal. The environmental-socio-economic factors at these sites are associated with the local sphere, the contributors' involvement, the project tasks and objectives, and the technology used.

The environmental impacts related to these sites are minor, since both of them are flooded with water, rendering mining idle. The mining activities at the Malaposta Open pit involve the extraction of gneiss of different densities and compositions. Currently, this open pit has flooded areas that are not subject to active mining. In return, these flooded pits, with a depth of about 80m, provide access to water through ramps. However, the presence of these water bodies creates a unique environmental condition suitable for testing and demo purposes for both the Muon telescope technology and the deployment of autonomous underwater robots. At the other site, the Urgeiriça Mine, both cut-and-fill mining and in-situ leaching techniques were used over time. Today, the entire mine is flooded, and the Santa Bárbara shaft has a water level of around 8 m depth. Consequently, the flooded mine provides a challenging and valuable environment for testing the AUV robot developed by INESC TEC for exploring and 3D mapping the mine.

On the other hand, the socio-economic factors associated with these Pilot Sites cover a wider interval of key aspects. To begin with, the mining activities carried out at the Malaposta open pit and the Urgeiriça mine contribute to local employment opportunities. The operations at these sites require skilled workers, technicians, and engineers, which results in jobs creation that ultimately boosts the local economy. Additionally, the presence of these Pilot Sites attracts technology providers, research institutions, and manufacturers to support the development and deployment of innovative technologies. This leads to collaborations and partnerships that benefit the local industry and enhance its competitiveness. Another crucial aspect encompasses innovative research. The involvement of organisations such as INESC TEC and Muon Solutions Oy in the Pilot Sites demonstrates the focus on innovation and research in the region. The development and testing of new technologies and methodologies at these

Pilot Sites contribute to scientific advancements and attract further investments in research and development. Infrastructure Development is also a noteworthy aspect of the socio-economic factors linked to the Pilot Sites. Both mines necessitate the presence of infrastructure such as storage facilities, power generators, telecommunications, and control rooms. The development and maintenance of these facilities can lead to infrastructure development and improvement in the surrounding areas.

An overlapping and essential field for environmental concerns and socio-economic factors is environmental protection. The sites' focus on underwater exploration and imaging in the flooded areas of the open pit and the mine demonstrates the commitment to environmental protection. Utilising such advanced technologies allows the project's aim to minimise environmental impact and develop sustainable mining practices.

The Malaposta Open Pit and the Urgeiriça mine provide unique environmental conditions suitable for testing and demo purposes. The involvement of various organisations contributes to employment generation, industry support, innovation, and research. Additionally, the project promotes infrastructure development and environmental protection. The abovementioned tasks and objectives focus on developing and validating technologies related to underwater muon imaging, autonomous exploration robots, and data export systems. The functional and non-functional requirements outlined for these tasks ensure the reliability and robustness of the technologies being developed. Overall, these Pilot Sites represent a significant opportunity for technological advancements in the mining industry and its socio-economic impact on the local communities.

5 Digital Solutions for Waste Exploration and Post-Mining Environmental Management

5.1 Geochemical Mapping of Soils and Mining Wastes in Lavrion Historic Mine Site – Post-Mining Environmental Management

Pilot Site 3 is located within the borders of the Lavrion Technological & Cultural Park (LTCP) in the city of Lavrion, Greece. Lavrion is located at Lavreotiki peninsula on the south-eastern side of the Attika prefecture. Ancient Greeks started mining and metallurgy in the Lavreotiki area around 3,000 BC. During the 5th century BC, Lavrion was a large-scale silver mining and metallurgy centre, providing the city of Athens with the necessary wealth for its cultural development and military superiority.

In fact, the whole region is full of ancient and modern mining galleries. Despite its small scale (about 10,000 inhabitants), Lavrion has been one of the most important industrial centres in Greece during the 19th and 20th centuries. It was built as a worker's settlement in the newly founded Hellenic State, partially following the "company town model".

The metallurgical and mining industry, as it developed in the wider area of Lavreotiki, is considered, worldwide, perhaps the most important source of soil pollution, especially regarding heavy metals.

The Pilot Site consists of a “polluted soil landfill site” (waste repository), constructed some 20 years ago to isolate a significant portion of heavily polluted soils from the general environment. The site was constructed on the basis of the “dry tomb”.

The main features of the repository include:

- Some 130,000 m^3 (estimated mass of almost 300,000 ton) of polluted soils contained a clean-up area of 50,000 m^2.
- Configuration of a selected area within the borders of L.T.C.P. as a landfill site.
- Dumping of soils within the landfill site.
- Main pollutants include Pb, As, Cd, Zn, Cu, Mn and Fe in different compounds (e.g., oxides, sulphides, etc.).

The repository has been engineered as follows (lower to upper levels):

- 4.5 mm thick protective non-woven polypropylene geotextile (800 gr/m^2).
- 0.8 mm thick (dry/wet) Geosynthetic Clay Liner (GCL) consisted of bentonite layer placed between two geotextiles with a hydraulic conductivity of $1{,}0\times10^{-11}$ m/s.
- 1.0 mm thick double-sided textured high-density polyethylene geomembrane.
- 10.0 mm thick 100% HDPE geosynthetic drainage layer.
- Non-woven polypropylene geotextile (250 gr/m^2).
- 1.0 m thick topsoil.

Soils within the repository typically include concentrations of iron, lead, and zinc in the order of % (greater than 10,000 mg/kg), concentrations of arsenic, copper, manganese and cadmium ranging from 0.1 to 1% and lower concentrations of antimony and molybdenum. (AMDC Technical Project, 2009)

According to the proposal, except from AMDC, the other contributors involved include GFT, ACC, INN, HMU and USAL.

5.1.1 Detailed Overview of the Tasks and Objectives

The targets and objectives of the Pilot Site may be divided into three individual phases. The main targets include the optimal area characterisation and the obtaining data on the valuable and exploitable ground composition and distribution information (exploration) to propose a valuable metal extraction method (extraction) and/or propose a management/remediation method for pilot application (waste management).

The main objectives related to each individual phase are further analysed below.

Exploration:

- Define the chemical and mineralogical composition of material/waste.
- Understanding of the repository geometry.
- Investigation of the potential for metal recovery.

Extraction/Processing:

- Exploitation of waste as an "ore".
- Assess the level of impact compared to other methods and/or remediation methodologies.
- Define available extraction methods.

Waste Management:

- Treat the contents of the repository as waste.
- Assess the level of impact compared to extraction and/or remediation methodologies.
- Define available management/remediation methods.

The main tasks that will be fulfilled for the proper demonstration of the Pilot Site include:

- T2.2: Exploration, electrification and extraction understanding and technical requirements.
- T2.3: Processing and waste management understanding and technical requirements.
- T4.7: Pre-classification of stockpiles materials and electromagnetics for exploration/waste management and drone magnetometry.
- T5.4: IIoT connection and Edge-to-Cloud connection platform.
- T6.4: Pilot Side 3: Greece.

T2.2 and T2.3 are dedicated mainly to identifying the functional and non-functional requirements of the Pilot Site. Those requirements are presented in par. 5.1.3 of the current deliverable. Also, those Tasks will help to understand the fundamental architecture of the digitisation process for fulfilling Pilot's objectives.

Task 4.7 Pre-classification of stockpiles materials and electromagnetics for exploration/waste management and drone magnetometry

This task is divided into the following subtasks.

- Subtask 1: It will be devoted to the design of data acquisition procedures from multi-sensor platforms adapted to the geometry and complexity of the repository, followed by the study of the different geophysical techniques that best adapt to the analysis of surface/interior homogeneity and other attributes of the waste deposited (e.g., composition).
- Subtask 2: It will develop data processing protocols received from the sensors of subtask 1.
- Subtask 3: Since AMDC possesses previous data (e.g., chemical, mineralogical composition, etc.) for the repository all aforementioned devices will be tested in order to determine the actual quality of the data obtained.

T5.4 IIoT connection and Edge-to-Cloud connection platform

This task will implement the interconnection between the Edge and the Cloud. Edge will consist of sensors that are responsible for the collection of measurements that need to be transferred to the Cloud through a gateway.

5.1.2 Used Technologies

The main technologies, divided by each mining/metallurgical phase that will be developed include:

Exploration Phase:

- Magnetic measurements, including:
  - Geospatial module.
  - Drone route software.
  - Geophysical inversion tools.
- Utilisation of LiDAR RGB cameras:
  - Flight planning software.
- Implementation of advanced geoelectrical methods:
  - Geophysical inversion tools.
  - Interpolation modules.

Extraction Phase & Waste Management Phase:

- Radar and Laser-Induced Breakdown Spectroscopy - LIBS measurements/Advanced geoelectrical methods
  - Geophysical inversion tools.
  - Interpolation modules.

    - Automated Confirmation Transaction Platform.
    - HSC-Sim software.
- Risk Assessment Tools.
    - Computer Based Models (Risk Calculator).
- Environmental/Social Impacts/Carbon Footprint Software, Life Cycle Assessment – LCA software.

IIoT connection and Edge-to-Cloud connection platform (HMU)

The implementation of the proposed Edge-to-Cloud connection will be contingent on the existing or planned network infrastructure within the mine. Currently, HMU maintains ongoing communication with ETAIREIA AXIOPOIISEOS KAI DIACHEIRISEOS TIS PERIOUSIAS TOU ETHNIKOU METSOVIOU POLYTECHNEIOU (AMDC), leading Pilot Site 3 in order to gather detailed information regarding the available communication technologies and accessible network infrastructure within the repository. This investigation aims to identify suitable communication technologies for the Pilot side.

The Lavrion historic mine site and the waste repository, as a surface structure, is located close to Athens city. The site possesses a 4G/5G coverage and Internet access.

As mentioned earlier, an exploration of the market is in progress to identify an IoT gateway solution that fulfils all the specified requirements. According to the Description of Action, the IoT gateway should provide the following features:

- Have the ability to support IoT communication protocols such as IEEE 802.11ah, Bluetooth, LoRa or other relevant standards to collect data from various IoT devices.
- Support WI-FI or any other communication protocol that will guarantee reliable and consistent connectivity to the internet.
- Contain a GPU that can accommodate minor AI computations.

The gateway that will be used in the Pilot Site 5 (Niederschlag mine) will also be suitable to be used in the Lavrion historic mine site.

5.1.3 Functional and Non-Functional Requirements

Functional requirements refer to the main objectives of the Pilot Site, i.e., what are the features to be built to fulfil the pilot's need (e.g., assess raw material/waste/product properties). Non-functional requirements refer mainly to quality criteria that have to be fulfilled by the product, i.e., the digital twin (e.g., security, availability, accessibility, etc.). The main functional and non-functional requirements for Pilot Site 3 are presented below for each mining/metallurgical phase:

Functional Requirements

Exploration Phase:

- Detect anomalous concentrations of recoverable material.
- Create a Digital Terrain Model (DTM) of sufficient resolution.

- Investigate the geologic structure of the deposits of interest.
- 3D models for identifying areas with a potential for a more convenient and safer material restoration/recovery set-up.

Extraction Phase:

- Assess waste (chemical/mineralogical) properties.
- Risk assessment/Impact assessment/Carbon Footprint on the extraction process.

Waste Management Phase:

- Assess waste (chemical/mineralogical) properties.
- Define optimum management/remediation alternatives.

Non-functional Requirements

Exploration Phase:

- Drones with suitable characteristics for magnetic data acquisition.
- Accurate readings of the background magnetic radiation from the site".
- High-quality cameras and sensors capable of granting the precision required for subsequent modelling.
- Data acquisition line with an adequate definition/depth ratio.
- Process time lapses compatible with established work rates.
- The potential of incorporating new functionalities.

Extraction Phase & Waste Management Phase:

- Level of accuracy - Extensibility/Potential of incorporating new functionalities.
- Compliance with Environmental Legislation.
- Compliance with Health & Safety Regulations.
- Stakeholders Engagement.
- Social Compliance.

5.1.4 Further Aspects

The Pilot Case in Lavrion involves several socio-economic aspects as those described below:

- In most European countries, the problem of contaminated soils from past mining and metallurgical activities is very acute. Urban expansion, population growth and the high cost of land lead to the need to use highly polluted areas for residential and recreational purposes, which creates considerable risks to human health while degrading the living standards. This phenomenon is observed in the area of Lavrion, where residences have been built next to piles of slag.
- The metallurgical and mining industry, as it developed in the wider area of Lavreotiki, is considered, worldwide, perhaps the most important source of soil pollution, especially regarding heavy metals.

- The high costs associated with soil decontamination either perpetuate the problem or lead to temporary and dubious in terms of quality and effectiveness solutions. The need to explore alternative methods of soil remediation or metal extraction is rather urgent, targeting both efficiency and cost reduction.
- Most of the metals and metalloids found in the soils of Lavrion, including the study area, are of high "ecological risk" due to their toxicity to mammals, including humans, but also due to their cumulative behaviour.

Environmental-socio-economic factors for geochemical mapping of soils and mining wastes in Lavrion

The Lavrion Historic Mine Site, located close to Athens city, is an open-pit mine with a rich history dating back to ancient times. The goal of the project is to analyse the socio-economic factors and environmental considerations at the Lavrion Historic Mine Site, specifically focusing on the implementation of digital solutions for waste exploration and post-mining environmental management. The use of technologies such as IIoT connection and an Edge-to-Cloud connection platform (HMU) will be exercised throughout the project, which will highlight the need for suitable communication technologies and the use of an IoT gateway solution.

The Lavrion mine has significant socio-economic importance for the local community and the wider region. Historically, mining activities at Lavrion have played a vital role in the development of the local economy, providing employment opportunities and contributing to the growth of the mining industry. The site has also been a significant source of mineral resources, particularly silver, lead, and zinc. The extraction and processing of these minerals have not only generated economic benefits but also contributed to the development of related industries such as metallurgy and manufacturing. However, the decline of mining activities at Lavrion has had adverse socio-economic impacts on the local community. The closure of the mine has led to job losses and economic stagnation in the region. The transition to a post-mining economy has been challenging, with the need for alternative employment and economic development sources.

Furthermore, the environmental legacy of the mining activities at Lavrion also poses socio-economic challenges. The site has significant waste deposits and the potential for environmental pollution. The management and remediation of these waste deposits require careful planning, technological interventions, and huge financial resources. Sustainable solutions for waste exploration and post-mining environmental management are crucial for the long-term socio-economic development of the Lavrion site and the surrounding communities.

The Lavrion mine presents unique environmental challenges due to its mining history. The extraction and processing of minerals have resulted in the accumulation of waste deposits and pollution of soil, water, and air. The mitigation of these environmental impacts is crucial to restore the ecological balance and enable sustainable land use in the area. The use of digital solutions for waste exploration and post-mining environmental management can significantly contribute to the restoration efforts at Lavrion. The use of IIoT connection and an Edge-to-

Cloud connection platform (HMU) allows for the collection of real-time data from sensors deployed across the site. This data can provide valuable insights into the extent of pollution, the behaviour of pollutants, and the effectiveness of remediation efforts.

The availability of 4G/5G coverage and internet access at the Lavrion facilitates the implementation of these digital solutions. The existing network infrastructure can support the communication requirements for data transfer between the Edge and the Cloud. This interconnection between the Edge and the Cloud is essential for real-time monitoring, analysis, and decision-making regarding waste exploration and post-mining environmental management. The IoT gateway used at the Niederschlag mine is also suitable for deployment at the Lavrion Pilot Site. This gateway fulfils the required features, including support for IoT communication protocols, reliable connectivity to the internet, and the ability to accommodate minor AI computations. The use of this gateway enables seamless integration of sensors and data collection devices, ensuring a robust and comprehensive approach to waste exploration and environmental management.

Digital solutions, such as IIoT connection and an Edge-to-Cloud connection platform, offer immense potential for waste exploration and post-mining environmental management. The availability of 4G/5G coverage and internet access at the site, along with the suitability of the IoT gateway used at the Niederschlag mine, ensures the feasibility and effectiveness of these digital solutions.

By leveraging these technologies and implementing suitable communication technologies, Lavrion can effectively address its socio-economic and environmental concerns. The use of real-time data collection, analysis, and decision-support systems can contribute to the restoration of the site, enable sustainable land use, and promote economic development in the region.

5.2 Multi-Source Data Fusion and Interpretation for Surveillance of Tailings Embankments

Testing in the Pilot Site at the Pyhäsalmi mine in Finland is coordinated by UOULU. The mine was opened in 1962 and produced copper, zinc and pyrite. The Pyhäsalmi deposit is over 1.9-billion-year-old Volcanogenic Massive Sulphide (VMS) deposit, and it forms an elongated accumulation of base metal sulphides stretching from the current erosional level down to 1400 m depth. Underground mining ended in autumn 2022, but reprocessing of stored tailing pond material is expected to continue above ground until 2025-2026. The Pyhäsalmi mine includes an underground mine and two open pit mines. One of the open pits is the original open-cast pit, which was opened in 1962 and remained in production until 1975.The second open pit was used for backfill rock extraction. In addition, the site has four tailing ponds (A, B, C and D). These are all in different stages of use, totalling an area of 150 ha.

The mine site is owned by the Pyhäsalmi Mine Oy company. Research and scientific activities at the site are facilitated and hosted by the Callio Lab research centre, which is coordinated by the multidisciplinary University of Oulu (UOULU/KSI) . The third operator on-site, in addition to the mining company and the University of Oulu, is the Pyhäjärvi town-owned Callio

Mine for Business Concept, which is developing new use and business cases utilising the mine site infrastructure.

For all project activities on-site and pertaining to the Mine.io Finland Pilot Site, the coordinating contact is:

- University of Oulu, Kerttu Saalasti Institute Callio Lab (UOULU/KSI).

5.2.1 Detailed Overview of the Tasks and Objectives

The task in 5.2 Multi-Source Data Fusion and Interpretation for Surveillance of tailings embankments is carried out by:

- University of Oulu, Oulu Mining School (UOULU/OMS).

The objective is to pilot a geophysical approach for monitoring the subsurface condition of tailings embankments. Currently, the monitoring of tailing embankments is generally done using point-source measurements, which is time and resource-intensive because tailings embankments are large structures. These structures must be regularly checked throughout the mine lifecycle and even after it is closed.

UOULU/OMS will develop and apply a combination of electric resistivity imaging (ERI) and active- and passive-source seismic imaging to map the subsurface structure of tailings embankment and retrieve hydrogeological and elastic parameters.

With the ERI system, an array of electrodes placed at the surface and/or boreholes in the target area retrieve electrical resistivity imaging sections (the output). For seismic imaging, both active and passive (virtual) seismic sources enable the mapping of the subsurface structures in terms of seismic velocities (body- and surface waves) via an array of geophones around the target area. The processing of seismic wave travel times and dispersion curves of surface waves gives the distribution of the seismic velocities (the output).

Further joint inversion and interpretation of the geophysical data will provide actionable intelligence in terms of physical and mechanical conditions of the structural element of the tailings embankment that are of interest in planning and decision-making in the industry. The interpretation will result in thematic maps and datasets for phreatic line, water flow, saturation of water, and elastic conditions.

Subtask 1 Electric resistivity imaging (ERI) of tailings embankment:
The implementation of non-invasive, quantitative, near-real-time ERI is conducted to assess the structural integrity of tailings embankments. The design and deployment of an ERI system are executed in a specific section of the tailings embankment to facilitate detailed evaluation.

Detailed tasks:

- Evaluate and define the domain target in Pyhäsalmi tailings area.
- Implement remote data acquisition and transmission.
- Installation and field measurement in Pyhäsalmi with electrodes placed on the surface or in existing boreholes to retrieve electrical resistivity imaging sections.

- Test continuous data acquisition and transmission.

Subtask 2 Seismic imaging with active and passive seismic sources of tailings embankment:
The application of non-invasive, quantitative, near-real-time seismic imaging is utilised for the comprehensive assessment of tailings embankments. The design and deployment of a seismic imaging system are carried out in a designated section of the tailings embankment to enable detailed analysis.

Detailed tasks:

- Implement remote data acquisition and transmission.
- Installation of an array of geophones around the domain target in the Pyhäsalmi tailings area.
- Test continuous data acquisition and transmission.

Subtask 3 Data pre-processing, processing and inversion modelling:
The task involves the processing of geophysical data to generate the electrical resistivity distribution and seismic velocity distribution maps or sections. The electrical response of the subsurface is interpreted as apparent resistivity. Seismic wave travel times and the dispersion curve of surface waves will be interpreted as the distribution of seismic velocities. Detailed tasks:

- Data pre-processing and filtering.
- Data processing & inversion modelling.
- Visualisation maps or sections.

Subtask 4 Multi-source data fusion
The further processing and interpretation of geophysical data are undertaken to derive hydrogeological and elastic parameters, thereby enhancing the overall understanding of the subsurface conditions. Mining operators will receive actionable intelligence that provides insights into the hydrogeological and mechanical conditions of the tailings embankment in the subsurface, facilitating informed decision-making.

Detailed tasks:

- Joint-inversion and interpretation of the geological, field and geophysical data.
- Output is image sections and datasets for phreatic line, water flow pattern, saturation, and elastic conditions.

5.2.2 Used Technologies

The digitalisation of operational mining activities will focus on the monitoring of tailings embankments, which are key structural elements in tailings facilities. For this, two geophysical techniques (electrical resistivity imaging and seismic imaging) are used to gather data from the subsurface of the tailings embankment and interpret it in terms of hydrogeological and elastic parameters.

In both techniques, the central unit is equipped with telemetry-based connectivity and a central database management system. An automated processing and inversion algorithm to be developed will produce a daily tomographic reconstruction of the subsurface using the dataset from the remotely accessed database.

UOULU/OMS will provide the equipment and instrumentation, which is tailored to the needs of the project. UOULU/KSI will coordinate with the Pilot Site stakeholders to arrange access and permissions to deploy the measurement systems. UOULU/KSI will also participate in the installation of the systems on-site.

5.2.3 Functional and Non-Functional Requirements

Requirements from the Pilot Site to the Technology Partner include the following:

Functional requirements include:

- The digitisation of electrical resistivity distribution in tailings embankments by using electrical resistivity electrodes as sensors.
- The digitisation of seismic velocities in tailings embankments by using geophones as sensors.

Non-functional requirements include:

- Pilot and demonstration program/deployment of geophysical imaging techniques, detailing the resources for deployment and task with responsibilities and timelines.
- Compliance with site requirements and permits: accessibility, fieldwork, safety due diligence (Job Safety Analysis & Safe Operating Procedures).

Requirements from the Technology partners to the Pilot Site (second step in first version not necessary) include the following:

Functional requirements include:

- Network connectivity (Ethernet) is available at the testing location.
- The power source is available at the testing location.

Non-functional requirements include:

- Coordination with mine operators to access the testing site.
- Providing site dataset and information about engineering and construction drawings of the embankment, digital elevation models, and material construction specifications.
- Personnel to assist in the installation of the testing equipment and deployment of sensors on site.
- Ongoing technical support during the testing period.

5.2.4 Further Aspects

Environmental-socio-economic factors for the Finnish Pilot Site – UOULU

The Pyhäsalmi mine site in Finland has significant socio-economic factors associated with it. Firstly, the mine has been an important source of employment for the local population since it was opened in 1962. Hence, the mining operations have provided job opportunities for both skilled and unskilled workers for decades, thus contributing to the economic development of the region. The closure of the underground mining operations in 2022 has led to the loss of jobs for many workers, although the reprocessing of stored tailing pond material is expected to continue above ground until 2025-2026, providing some employment opportunities in the interim. The mine site is owned by Pyhäsalmi Mine Oy, which is responsible for the overall management of the site. The company has invested significant resources in the development and operation of the mine, contributing to the local economy through direct and indirect impacts. The mine operations have generated revenue through the production of copper, zinc, and pyrite, which has supported the local economy and contributed to national exports.

The presence of the University of Oulu (UOULU) and the multidisciplinary Callio Lab research centre at the site also has important socio-economic implications. The University of Oulu facilitates research and scientific activities at the site, bringing together experts from various fields to collaborate on innovative projects. This not only contributes to scientific knowledge and advancements but also provides opportunities for students and researchers to gain practical experience in a real-world setting. The research activities at the site have the potential to attract funding and investment, supporting the development of new technologies and business ventures in the mining sector. Additionally, the Pyhäjärvi town-owned Callio Mine for Business Concept is another on-site operator, focusing on developing new use and business cases that utilize the mine site infrastructure. This indicates that the site has the potential to be repurposed for other economic activities beyond mining, which could further contribute to the local economy and create new job opportunities.

The Pyhäsalmi mine site has significant environmental considerations due to its history of mining operations. The extraction of copper, zinc, and pyrite has led to the generation of large amounts of tailings, which are stored in tailing ponds on-site. The presence of four tailing ponds (A, B, C, and D) indicates the scale of the environmental impact of the mining operations. These tailing ponds cover an area of 150 hectares and require careful management to prevent any contamination of the surrounding environment. One of the objectives of the project at the site is to develop a geophysical approach for monitoring the subsurface condition of tailings embankments. This is important for ensuring the stability and safety of the tailings ponds, as well as identifying any potential risks or issues that need to be addressed. By developing a non-invasive and near-real-time monitoring system, it will be possible to detect any changes in the subsurface conditions and take appropriate actions to mitigate any environmental risks.

The use of electric resistivity imaging (ERI) and seismic imaging techniques for monitoring the tailings embankments is a step towards more sustainable and environmentally friendly mining practices. By implementing these technologies, it will be possible to gather data on the hydrogeological and elastic parameters of the tailings embankments, enabling a better understanding about the performance of tailings facilities. This will allow for more effective planning and decision-making in the management of tailings facilities, with a focus on minimizing environmental risks and promoting sustainable practices.

The Pyhäsalmi mine site in Finland has significant socio-economic factors and environmental considerations associated with its activities. The site has been a source of employment and economic development for the local population, although the closure of underground mining operations has led to job losses. The presence of the University of Oulu and the Callio Lab research centre provides opportunities for research, innovation, and collaboration, contributing to scientific knowledge and supporting the development of new technologies and business ventures. The site also has significant environmental considerations, particularly in relation to the storage and management of tailings.

6 CONCLUSIONS AND NEXT STEPS

The Deliverable 2.1 (D2.1) describes each Pilot Site and its associated technology. The different Pilot Sites and technology providers are at different stages of defining their requirements. Thus, at the beginning of the work in the Work Package 2 (WP2), the Pilot Sites and Technology Partners were brought together to define the relevant tasks . It is always a challenge to bring together so many different partners and technologies. This initial process took longer than expected. The specified tasks were first defined between the different Pilot Site leaders and Technology Partners within the project. Functional and non-functional requirements were then defined for each technology that will be implemented in the Pilot Sites. The difficulty in defining the requirements was largely due to the undefined technologies being developed and tested within the project. Therefore, the list of functional and non-functional requirements is not complete and will be completed within the next year, following the progress of the project. On the other hand, the technical WPs (for instance, WP3, WP4 and WP5) started their work in Month 7 and the resulting knowledge of the developed technologies will be incorporated into all requirements and task descriptions of D2.1 .

The next step is to bring all requirements into a uniform structure within the GitLab cloud infrastructure of GFT Italia SRL. This will help to better structure the requirements of the Pilot Sites and Technology Partners, as well as prepare them for the upcoming work. The results of D2.1 will be used in the technical WPs (WP3, WP4, WP5 and WP6) responsible for the creation of all components of Mine.io. In addition, WP7 will start the validation phase at the Pilot Sites, followed by the deployment of Mine.io tools at the Pilot Sites. As the other WPs start, new requirements will emerge and will be collected in WP2 and D2.1.

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