MINE.IO
A Holistic Digital Mine 4.0 Ecosystem

Mine.io Architecture & Digital Framework for the Digital Mine

MINE.IO Final Event Workshop
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At a glance

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3. High-Level Reference Architecture (HLRA)
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Challenges in Modern Mining Operations

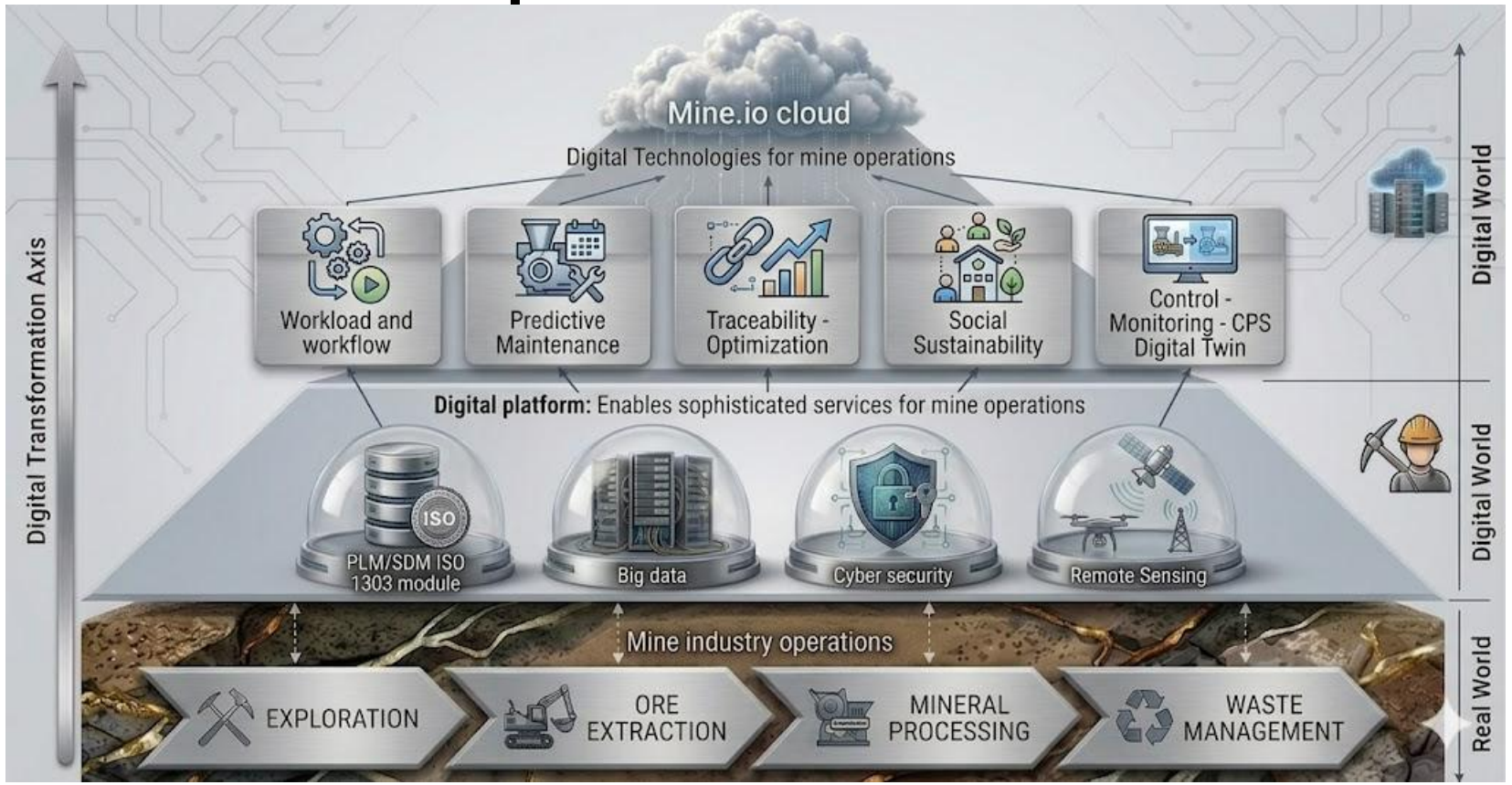
- Fragmented data ecosystems across mining sites
- Limited interoperability between systems and stakeholders
- Increasing complexity of environmental, operational, and safety requirements
- Need for real-time decision-making under harsh and distributed conditions

The Gap – Lack of Digitalization

- Legacy systems and siloed data
  - No existing data form mine operations
  - If data exists are siloed
- Limited adoption of real-time data pipelines
- Absence of unified data governance and standards
- Inefficient data exploitation for predictive and prescriptive analytics

The Vision – Mine.io Concept

- A pathway to digital transformation of mine industry
  - Connect the mine operations with the digital world
- Open, interoperable, and scalable digital platform
  - Supporting mine operations with innovative technologies and services
  - Edge-to-cloud integration for data acquisition and processing
- Layered approach



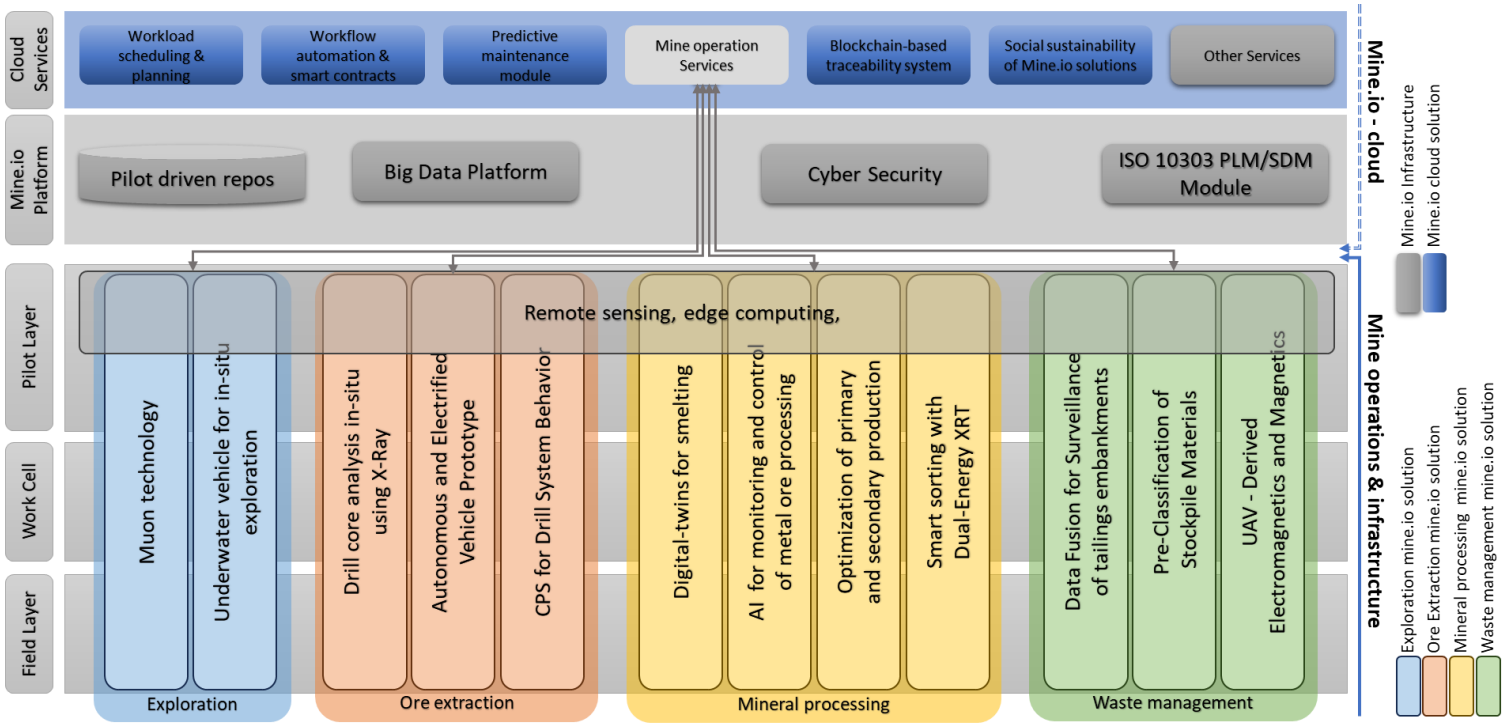
The Approach – Layered Architecture

Define a modular and scalable architecture:

- Decoupling of data acquisition, mine infrastructure, and services
- Enabling incremental integration of new pilots and systems
- Providing innovative Mine.io technologies for the mining operations
- Supporting cross-site and cross-domain interoperability
- Supporting cloud services
  - Proposed by Mine.io project
  - Provide standardized data access and integration with external services

Mine.io High-Level Reference Architecture

- Offered Technologies pillars in the mine layer
- End-to-end data flow:
  - End to end flow from edge – platform – services
- Integration of heterogeneous data sources
- Security-by-design and governance mechanisms
- 3 Layer approach:
  - Mine Physical operations Layer
  - Mine.io platform Layer
  - Cloud Service Layer



HLRA: Mine physical operations Layer

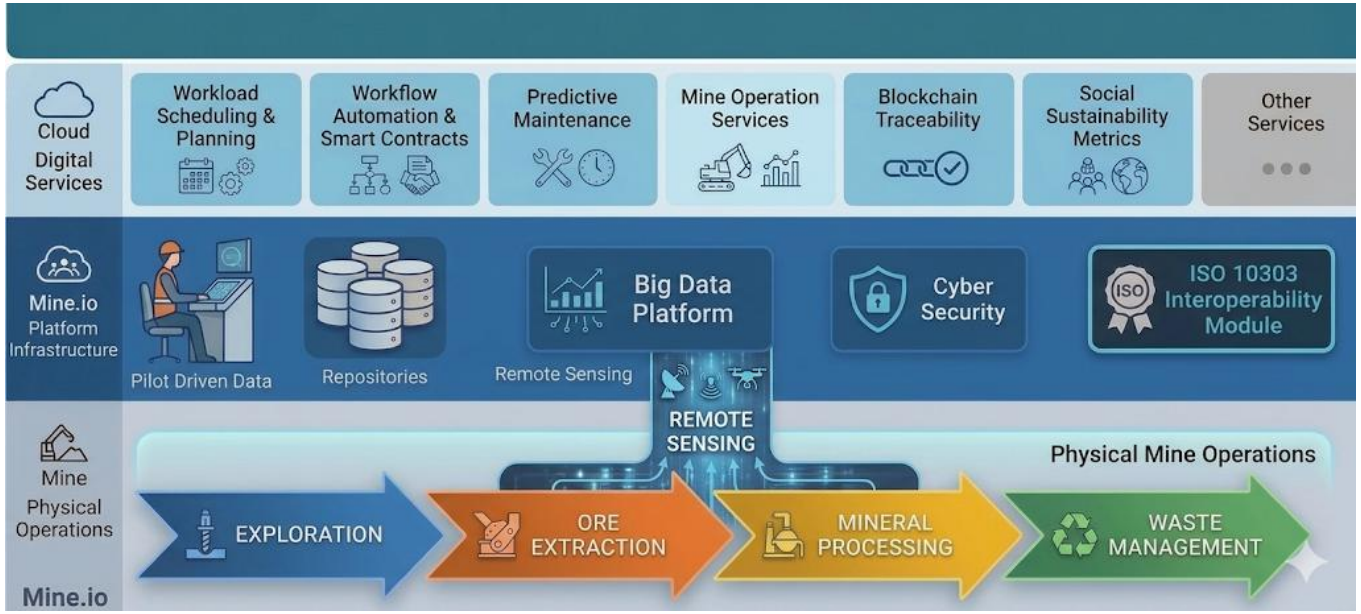
Operation Layer: Data Generation at Source

- Mining operations
  - Exploration, ore extraction, mineral processing, waste management
- Support mine operations with Mine.io technologies
- Infrastructure (*field tier*)
  - Drill rigs, TSL, furnace systems, IoT sensors, robots
- Data acquisition and control (*work cell tier*)
  - UAV, control units
- Data Preprocessing, utilization and monitoring (*pilot tier*)

HLRA: Mine.io Platform Infrastructure Layer

Enabling Data Integration & Management:

- Remote Sensing and Edge Computing
- Data Storage and Availability
  - Mine.io Big Data Platform
  - Repositories (pilot driven or cloud based)
- Interoperability and Data Models
  - ISO 10303 PLM/SDM Module
- Security and Governance

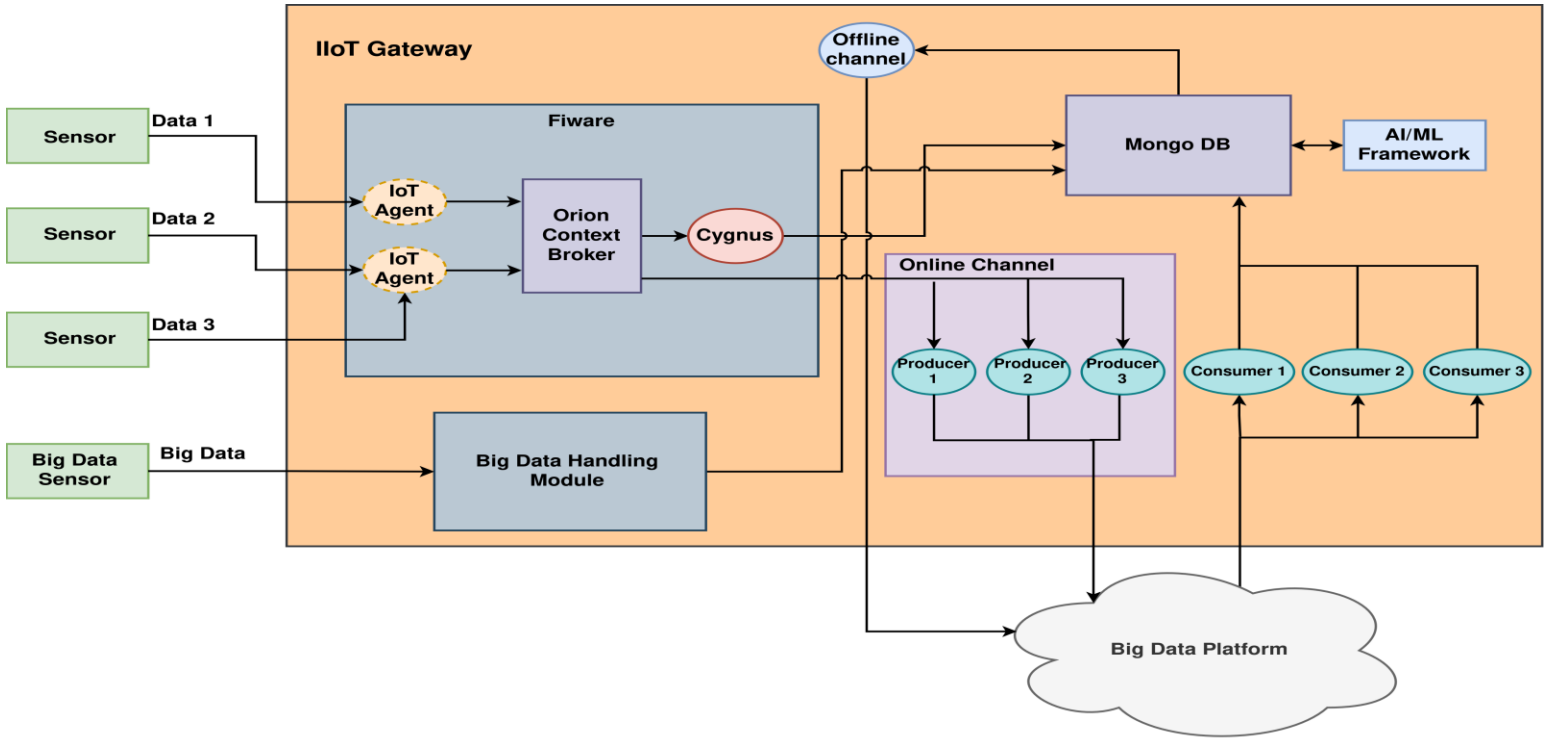


HLRA: Platform Layer – *Edge computing*

- Enables integration of diverse IoT devices, local systems, and pilot-specific data sources within a common architecture
- Based on FIWARE approach
  - Collect data from various sources
  - Support real time data acquisition and streaming
  - Support environments with limited internet connectivity
- Monitoring capabilities of mine operations
- Pipeline from mine to the platform
  - Real-time pipeline
  - Non-real-time pipeline
  - Big Data pipeline
- Utilize synchronous and asynchronous communication channels provided by the Mine.io Big Data Platform

HLRA: Platform Layer – *Edge computing*

- Bridge between pilot systems and the BDP
- IIoT Gateway as the integration hub
- FIWARE-based sensor data ingestion
- Separate channels for real-time, offline, and large-volume data
- Connector-based communication with the BDP



HLRA: Platform Layer – *Data Storage (BDP)*

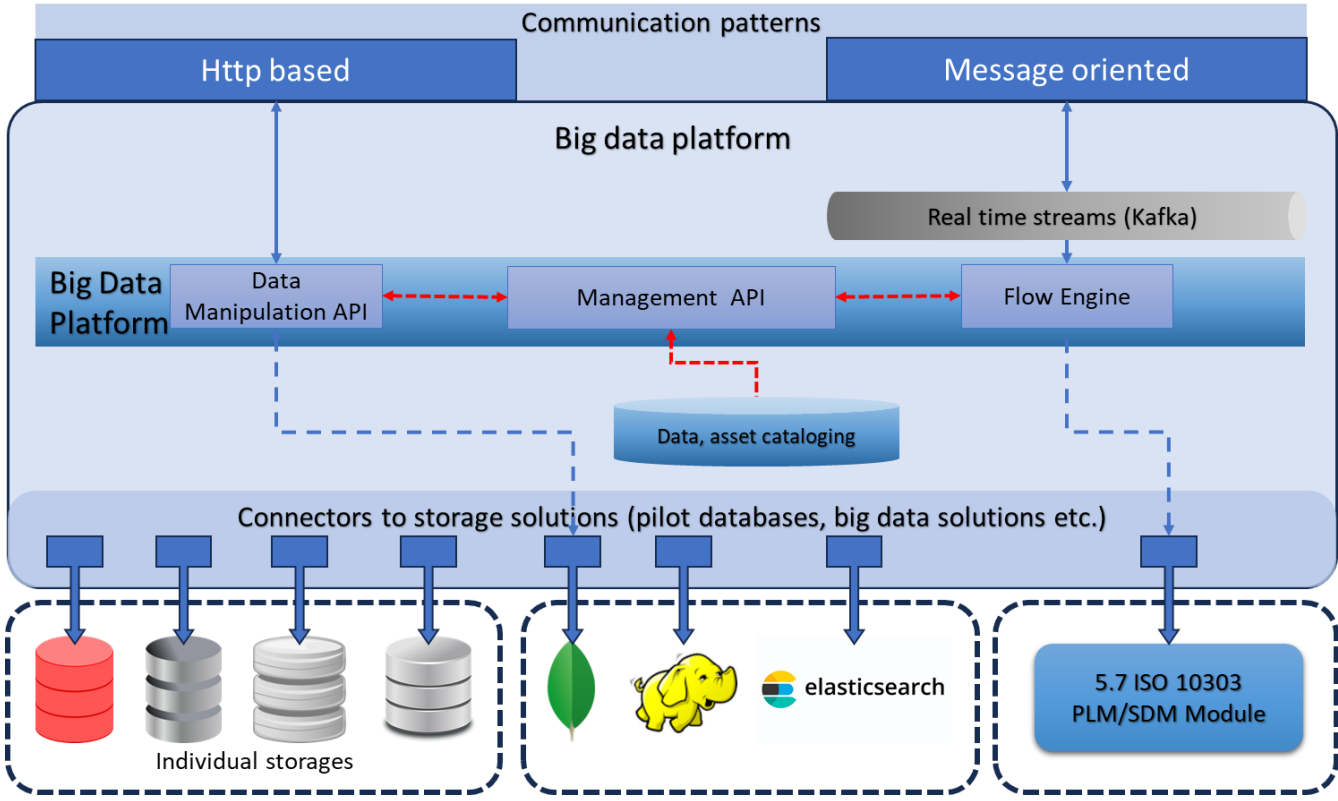
Challenges:

- Data heterogeneity
  - Sensorial, images, 2D-3D, files
- Individual data storages (siloed solutions)
- Lack of interoperability
  - No common access to the data
  - No data indexing – availability
- Different types of data
  - Stream of real time data, data batches
- Data Consistency – Availability – Persistence

HLRA: Platform Layer – *Data Storage (BDP)*

Layered approach for Big Data Platform

- Communication layer:
  - Supports two different communication patterns: synchronous and asynchronous (real-time data streaming and historical data)
- Management layer:
  - Enables indexing and searching
  - Support dynamic flow definition and execution
- Connectors layer:
  - Enables storage solutions and system interoperability
  - Expandable list
- Storage layer: Support a variety of storage solutions (individual and commercial ones)

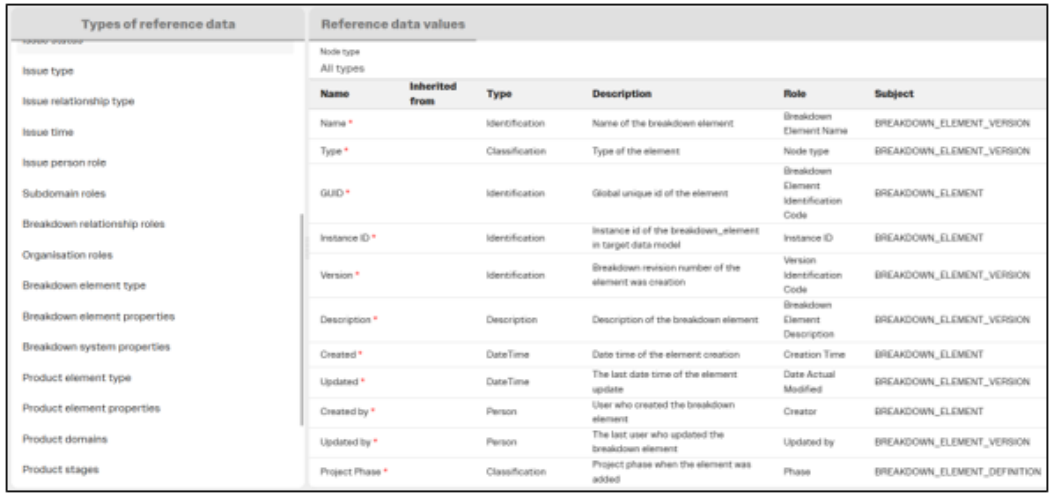


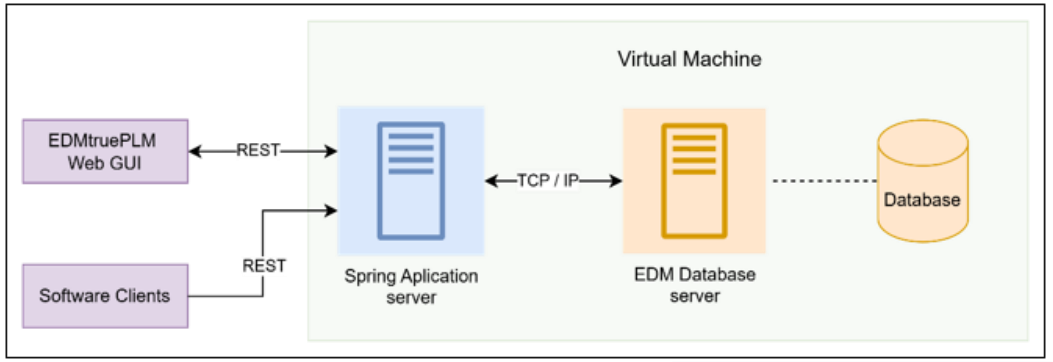
HLRA: Platform Layer – *Security & Governance*

- STRIDE threat analysis and DREAD risk prioritization across the full Mine.io component landscape
- Keycloak IAM providing least-privilege access control across all platform actors — sensors, autonomous machinery, operators, and subcontractors
- Cyber-Secure autonomous machines:
- DDS security stack: PKI-based authentication and AES-GCM-GMAC encryption on the autonomous vehicle interface
- Runtime monitoring for semantic validation of control commands, independent of cryptographic enforcement
- Privacy-preserving ABAC via homomorphic encryption: authorization decisions without exposing underlying user attributes

HLRA: Platform Layer – *Interoperability& Data Models*

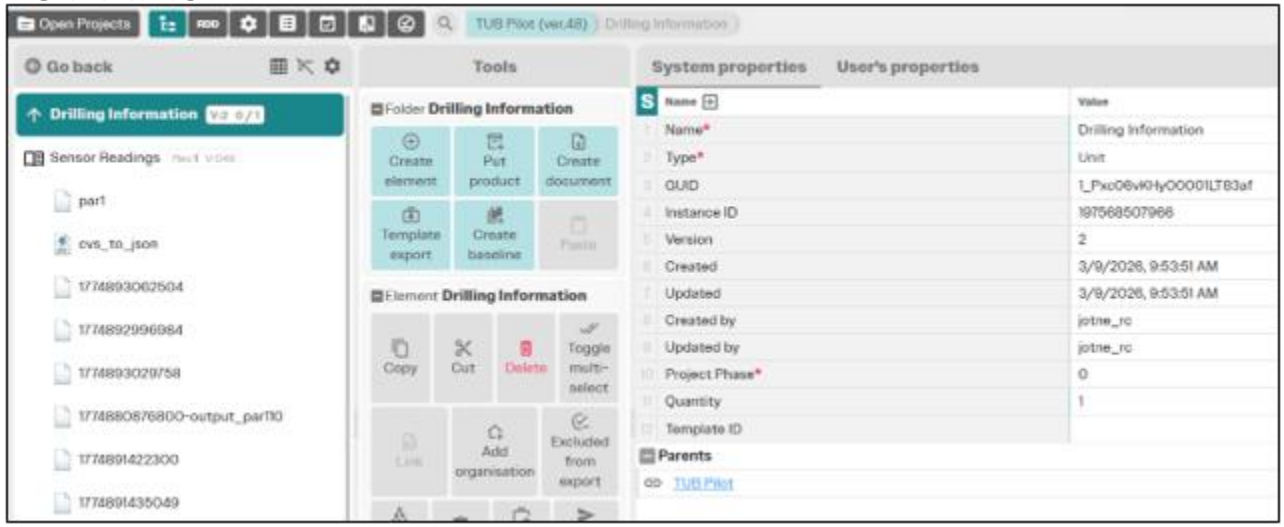
- The PLM Module is a central ISO 10303 repository for project and product data.
- The Mine.io objective of product data management extends EDMtruePLM into a cloud-capable IoT repository with rich data exchange capabilities.
- The repository is the core component of the PLM Module. Contains:
  - Product data, reference data, and system data
  - Archived models
  - The queries to update and retrieve the data.





HLRA: Platform Layer – *Interoperability & Data Models*

- The EDMtruePLM repository acts as a central integration point
  - RESTful APIs for seamless machine-to-machine communication
  - Ensures interoperability by using the ISO 10303 (AP239 PLCS) standard
  - Enables consistent product lifecycle data exchange across heterogeneous systems
- Data is transferred to the PLM module via REST APIs
- The architecture supports both:
  - Real-time data ingestion (online streaming)
  - Historical data access (repository storage)



HLRA: Service Layer

From Data to Value

- AI/ML models for predictive maintenance
- Workload scheduling
- Workflow automation
- Blockchain traceability
- Social Sustainability
- Visualization dashboards and reporting tools
- APIs for third-party services and stakeholder access

Closing the Loop – *Value & Impact*

- Improved operational efficiency and reduced downtime via:
  - *real-time, edge-to-cloud data processing and predictive analytics*
- Enhanced sustainability and environmental monitoring with:
  - *continuous monitoring and data-driven resource optimization*
- Data-driven decision-making across the mining lifecycle through:
  - *integrated and interoperable data ecosystems*
- Scalable and reusable digital infrastructure for future pilots by:
  - *supporting seamless integration of new pilots, systems, and services*
- Enhanced data accessibility and discoverability leveraging:
  - *asset cataloguing, Open APIs, and standardized data models (ISO 10303)*

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Thank you for your attention!

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