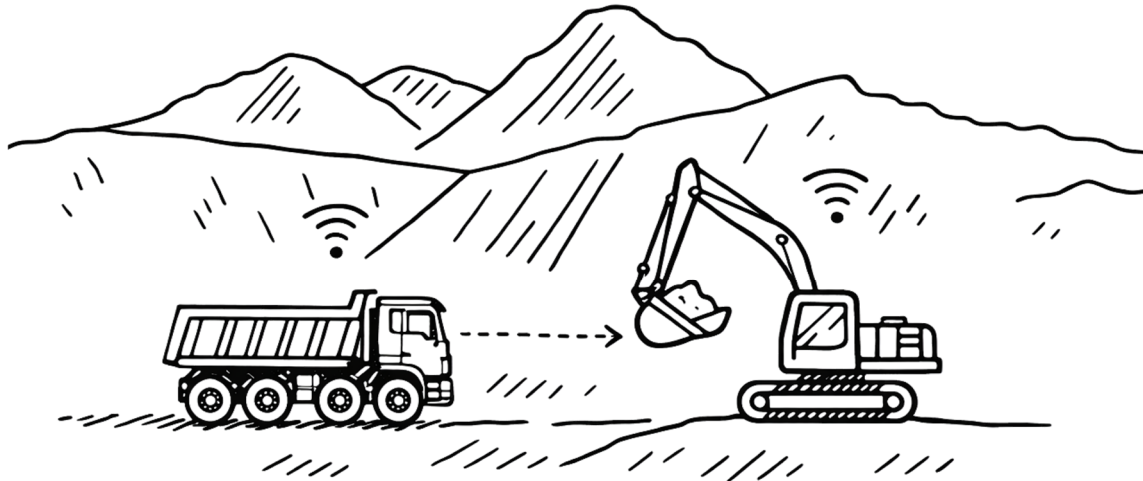




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Interoperability for autonomous machines and vehicles in mining

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Summary

This report summarizes the key findings from the Vinnova-financed project carried out within the framework of the Advanced Digitalization program. The project investigated interoperability in autonomous transport systems in mining, with respect to the integration of equipment from various suppliers and the coordination of both autonomous and manually operated machinery within shared operational contexts. The results demonstrate that while the introduction of autonomous mobile machines and digital solutions is progressing, significant interoperability challenges remain, particularly concerning data exchange, system compatibility, and the safe co-existence of mixed fleets within AOZ. The project identified several architectural principles and strategies to address these barriers, including the adoption of open standards, modular system interfaces, and collaborative development approaches involving multiple stakeholders. Case studies and technology reviews conducted during the project highlight both the current limitations of existing systems and the potential for future advances, such as improved efficiency, safety, and flexibility in mining operations. This summary is intended to provide actionable insights and recommendations for industry actors aiming to implement robust, future-proof interoperable solutions in autonomous mining transport.

1. Introduction

The mining industry is undergoing a significant transformation, driven by rapid advances in automation and digitalization. The integration of autonomous mobile machines and intelligent systems has the potential to revolutionize operational efficiency, safety, and sustainability across mining operations. As companies strive to adapt to evolving market demands and environmental considerations, the ability to implement interoperable solutions that allow different machines and systems to work seamlessly together has become increasingly vital.

This report presents a comprehensive analysis of the current state of autonomous transport systems within the mining sector, with respect to the challenges and opportunities associated with interoperability between equipment from different manufacturers and across various operational environments. It explores the latest technological developments, assesses existing solutions, and outlines overarching architectural principles designed to support the development of future-proof, collaborative transport processes in mining.

1.1. Background

Mining operations and extraction sites play an essential role in society, yet they are highly energy-intensive and encompass complex processes of material handling, sorting, and transportation. The industry is challenged by intensifying competition and shrinking profit margins, while simultaneously facing a paradigm shift driven by electrification and automation. Increasingly, commercial mining operations have begun introducing autonomous solutions, with one or more mobile machines operating without drivers in selected sub-processes. However, integrating these technologies into existing workflows presents significant challenges, as new digital and physical infrastructure, processes, tools, roles, and stakeholders must be managed and developed. A key aspect is interoperability, meaning the ability for autonomous solutions to coexist and collaborate with other systems. This includes both autonomous and manually operated machinery within the same process and physical space. However, current commercial solutions remain very limited.

The project “Interoperability for autonomous machines and vehicles in mining” aims to deepen understanding that enable effective collaboration between autonomous and manually operated machines from different suppliers within the mining industry. The focus is on identifying the main interoperability challenges and establishing overarching architectural principles, ensuring that machines and systems from diverse actors can work together in the same processes and physical environments.

This final report from the project presents insights into the state of the art, assesses interoperability, and outlines architecture principles for developing interoperable autonomous transport systems in mining.

1.2. Purpose and goal

The purpose of the project was to contribute to the development of autonomous transport systems for increased cooperation and interaction between autonomous vehicles and machines from different brands and between several areas of operation and systems in the transport process within the mining industry. The project’s goal was to create new knowledge about overall architectural principles to enable the integration of the interoperable autonomous transport solutions of the future.

1.3. Scope

The scope of this project is the **transport of blasted material within an active mining site**, focusing on internal logistics rather than outbound material flows. The transport process begins at the blasting and loading locations within the mine and ends at designated receiving points, such as crushers, stockpiles, or intermediate processing facilities, also located within the mine site (see Figure 1).

The emphasis is on **internal haulage operations**, including the movement of ore, waste rock, and potentially acid-generating (PAG) material. Logistics activities outside the mine site, such as transport to external processing plants or customers, are explicitly excluded from the scope.

The project concentrates on scenarios where **autonomous and manually operated mobile machines coexist**, either simultaneously or sequentially, within shared physical areas. These scenarios are representative of current and near-future mining operations, where automation is introduced incrementally and must integrate with existing processes, equipment, and organizational structures.

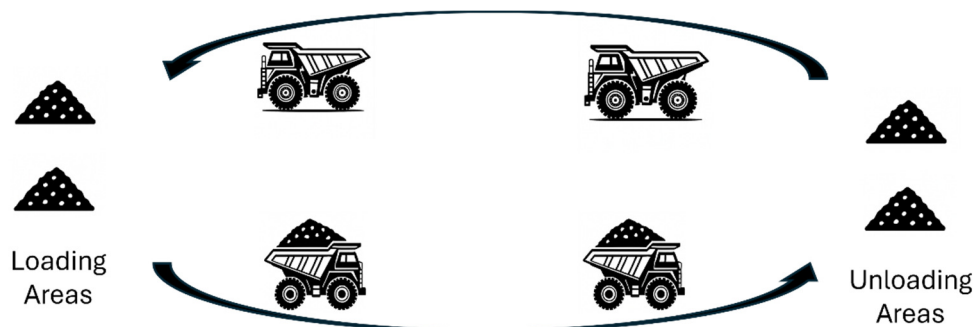


Figure 1 High level target operation of the project

1.4. System of interest (SOI) and system context

Definition of the system of interest

The System of Interest (SOI) in this project is the automated transport operation within the mine, encompassing the coordinated execution of loading, hauling, and unloading activities performed by mobile machines. The SOI is defined from the perspective of interoperability and focuses on how autonomous and manually operated machines, together with supporting digital systems, enable safe and efficient transport processes.

The SOI includes not only the physical mobile machines, but also the digital and control systems that plan, coordinate, supervise, and safeguard transport operations. The SOI is therefore socio-technical in nature, combining physical assets, software systems, communication infrastructure, and operational procedures.

SOI boundary and near environment

Within the scope of this work, the SOI comprises the following core elements:

- Mobile machines, such as haul trucks and loaders, operating autonomously or manually
- Autonomous Machine Systems (AMS), which automate machine behavior and execution

- The Fleet Management System (FMS), responsible for dispatching, coordination, and operational optimization
- The Safety System, including mechanisms that define and enforce Autonomous Operating Zones (AOZ)

Surrounding the SOI is a near environment of systems and functions that interact with, support, or constrain the transport operation but are not considered part of the SOI itself. These include:

- Diagnostics and condition monitoring systems
- Maintenance management systems, such as work shops, energy supply/refueling stations
- Digital infrastructure, such as communication networks and localization services
- Mining management and planning systems
- Process equipment, including crushers, conveyors, and silos

These systems influence the SOI by providing information, constraints, and services, but they remain operationally and architecturally distinct.

Multiple SOIs and system-of-systems perspective

As mining operations evolve, it can be expected for multiple instances of the SOI to coexist at a single site. Each equipment manufacturer typically provides its own proprietary solution for autonomous operation, including AMS, safety mechanisms, and supporting digital infrastructure. Each such solution can be regarded as a separate SOI instance.

When these SOI instances operate within the same mine, they become constituent systems (CS) of a larger system-of-systems (SoS). The constituent systems retain a degree of operational and managerial independence, while collectively contributing to the overall transport capability of the mine.

This SoS perspective is central to the project. Interoperability challenges arise not within a single SOI, but between multiple SOIs, particularly when machines from different manufacturers must share physical space, coordinate traffic, or interact during loading and unloading operations. Addressing these challenges requires architectural principles and coordination mechanisms that go beyond individual systems.

Architectural view of the SOI

Figure 2 provides a high-level architectural view of the SOI and its interaction with surrounding systems. The figure illustrates how mobile machines are controlled by Autonomous Machine Systems, coordinated by a Fleet Management System, and constrained by safety mechanisms, while interfacing with external systems for diagnostics, maintenance, digital infrastructure, and overall mine management.

This architectural view is not intended to represent a complete system design, but rather to clarify roles, responsibilities, and interaction points. It serves as a reference for identifying interoperability requirements and for structuring the functional domains described in the following section.

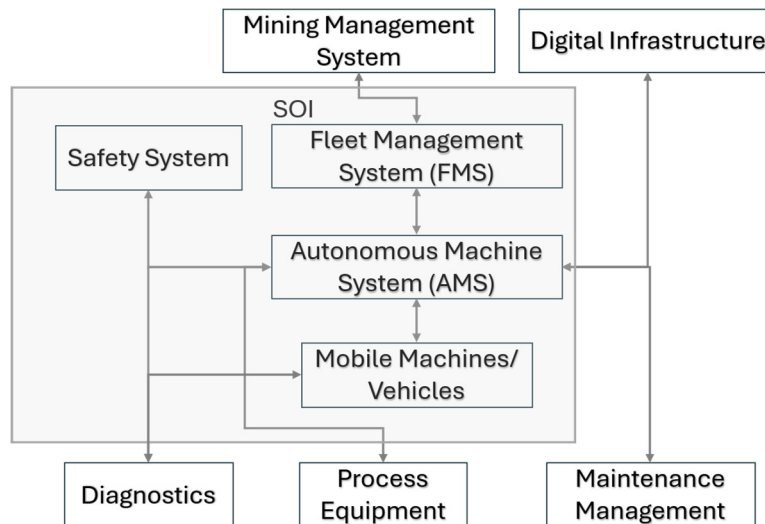


Figure 2 System of Interest and relation of functional domains

1.5. Functional domains and reference architecture

Autonomous transport systems in mining consist of a set of recurring functional domains, each responsible for a distinct class of functions required for safe and efficient operation. To clarify these functions and support interoperability analysis, the systems studied in this project have been structured into a reference domain architecture.

The proposed categorization aligns with relevant international standards, including ISO 23725:2024 and ISO 17757:2019, while extending them where necessary to reflect observed industrial practice and interoperability needs. The intent is to describe functions in a way that is structured, supplier neutral, and suitable for multi-OEM environments.

The functional domain categorization and descriptions presented in this section constitute a direct outcome of the project. They provide a common architectural reference that supports analysis, comparison, and future development of interoperable autonomous transport solutions in mining.

The identified functional domains include:

- Mine Management System, responsible for planning, scheduling, and geospatial definition of operations
- Fleet Management System (FMS), providing dispatch, mission level coordination, and production monitoring
- Safety System and Autonomous Operating Zone (AOZ), defining operational boundaries and safety conditions, and performing shutdowns if safety cannot be maintained
- Autonomous Machine System (AMS), a conceptual abstraction for automating machine behavior and execution, including traffic coordination
- Process Equipment Systems, such as crushers, silos and conveyors interacting with transport operations
- Digital Infrastructure, including communication and localization services

Together, these domains form a reference architecture that is used throughout the report to analyze interoperability challenges, identify architectural principles, and evaluate alternative coordination strategies.

1.6. Expected effects and result

To address the mining sector's requirements for interoperability amongst autonomous machines, it is essential to thoroughly assess how the industry's needs are currently being met by existing solutions and ongoing initiatives. This involves identifying where these efforts succeed and where gaps remain, ensuring a comprehensive understanding of the landscape. Furthermore, a deeper knowledge of the entire mining process is crucial, particularly regarding how autonomous systems and their associated digital infrastructure should be developed and incorporated into present-day operations and workflows. This greater insight will aid in facilitating smoother transitions and integrations. In addition, it is vital to establish a holistic system-of-systems architecture and set out clear principles for interoperability. Such an approach will support seamless collaboration between autonomous mobile machines from various manufacturers, ultimately enhancing the mining environment's efficiency and adaptability.

1.7. Terminology used in this document

- **Autonomous Haulage System (AHS):** An autonomous system enabling the operation of haul trucks without onboard human drivers. An AHS performs perception, navigation, motion control, and execution of haulage tasks for haul trucks, and exchanges task, state, and production data with fleet- and operations-level systems.
- **Autonomous Machine System (AMS):** An autonomous system enabling the operation of a specific type of mobile machine without an onboard human driver, including perception, navigation, task execution, and machine control.
- **Autonomous Operating Zone (AOZ):** A designated area and set of operational conditions in which specified mobile machines are authorized to operate in autonomous mode. A site may contain multiple AOZs with different rules and machine permissions.
- **Driver:** A human operator physically present in and controlling a mobile machine.
- **Fleet Management System (FMS):** A system responsible for planning, coordinating, monitoring, and optimizing the operation of vehicles and mobile machines in a mining operation, based on objectives and constraints from mine management system. The FMS may dispatch and coordinate both manual and autonomous operations.
- **Geospatial Analytics:** Collecting, analyzing, and visualizing data that has a geographic or spatial component.
- **Loading Machines:** Excavators and/or wheel loaders.
- **Mine Management System:** The system(s) responsible for defining the spatial, temporal, and production objectives and constraints of the mining operation, including material movement targets, mine geometry, and operational plans.
- **Mobile machines:** Self-propelled machines and vehicles capable of independent movement, including haul trucks, cars, tracked excavators, and wheel loaders. Mobile machines may be manually operated, teleoperated, or autonomously operated.
- **Operator:** A human responsible for supervising, teleoperating, or authorizing the operation of a mobile machine.
- **Virtual Driver:** The onboard or remote autonomous control function that performs the driving task normally carried out by a human driver.

2. Methodology

In this chapter, the methodology used in the project is outlined. As described in the previous chapter, the project aimed at identifying architectural principles that enable interoperability between autonomous vehicles in the mining industry. Therefore, the methodology is based on best practices for system architecting. However, as is always the case, generic best practices need tailoring to the specific problem at hand. This chapter thus describes what those best practices are, and how they were adapted and used in the project.

2.1. Architecting best practices

Over the last few decades, considerable progress has been made in clarifying what an architecture is, and how to perform architecting. The results have been codified in three engineering standards by ISO/IEC/IEEE: The 42010 standard describes architecture descriptions, 42020 architecture processes, and 42030 architecture evaluation. In this section, these standards are briefly summarized.

Architecture descriptions

The 42010 standard defines an *architecture* as “the fundamental concepts or properties of an entity in its environment and governing principles for the realization and evolution of this entity and its related life cycle processes”. However, the architecture itself is mostly intangible and embodied in a system. The tangible representation of the architecture is called an *architecture description*, which is defined as a “work product used to express an architecture”. The activity of *architecting* thus largely evolves around the creation, refinement, and analysis of architecture descriptions, which are then used to guide detailed design and development of the system.

For complex systems, there are always many different *stakeholders* who have different *concerns*, meaning that they regard different matters as relevant and important. The objective is then to find an architecture which balances those concerns in a reasonable way.

Due to the complexity of the system and the number of stakeholders and concerns, it is impractical to capture everything at once. Therefore, architecture descriptions are typically structured as a set of *views*, where each view captures certain related aspects of the architecture. The view can be presented as, e.g., text, informal drawings, or as models in a certain modelling language.

Often, similar concerns occur in many systems, and it is then practical to reuse the way they are described across architecture descriptions. A *viewpoint* is a “set of conventions for the creation, interpretation and use of an architecture view to frame one or more concerns”. A viewpoint is to look at the problem from a certain perspective, and the view is what you concretely see from that perspective. One can think of the view as an instance of a viewpoint.

Sometimes, a set of viewpoints is gathered in an *architecture framework*, which provides a standardized structure of architecture descriptions in a certain context. This approach was pioneered in the defense sector and later generalized in, e.g., the Unified Architecture Framework, UAF (Hause et al., 2017). Typically, these frameworks are intended for a whole organization employing many different interconnected systems, for which the term *enterprise architecture* is often used (Zachman, 1987).

Architecture processes

The 42020 standard details processes and activities that are relevant to perform as part of architecting. The three core processes are architecture conceptualization, evaluation, and elaboration. In addition, processes for management, governance, and enablement are also provided.

The purpose of architecture *conceptualization* is “to characterize the problem space and determine suitable solutions that address stakeholder concerns, achieve architecture objectives and meet relevant requirements”. This leads to a clear understanding of the problem, and what stakeholder concerns need to be addressed. It also defines the key concepts and properties and the trade-offs between them, as well as identifying candidate solutions.

Architecture *evaluation* has the purpose “to determine the extent to which one or more architectures meet their objectives, address stakeholder concerns and meet relevant requirements”. This shows how well the architecture addresses different stakeholder concerns, and identifies costs, risks, opportunities, and trade-offs associated with implementing the architecture.

The architecture *elaboration*, finally, is carried out “to describe or document an architecture in a sufficiently complete and correct manner for the intended uses of the architecture”. The outcome of this is an architecture description, consisting of different views and models.

Architecture evaluation

The 42030 standard describes a generic framework for evaluating architectures and can be used to support the architecture evaluation process described in 42020. The evaluation is performed in three tiers:

1. *Analysis* examines key attributes of an architecture along a certain dimension, such as cost, performance, etc.
2. *Value assessment* connects the analysis results to the value it provides to stakeholders, in relation to their concerns.
3. *Evaluation synthesis* combines multiple value assessments to determine to what extent overall objectives are satisfied.

2.2. Lifecycles and quality attributes

Understanding the stakeholders and their concerns is vital in architecting, since this is what determines if architecture solutions are good or not. Often, the concerns can be connected to different stages of a system lifecycle and be expressed as quality attributes. For these two aspects, there are also engineering standards that give guidance.

The 15288 standard focuses on what processes an organization needs to carry out to support a system’s lifecycle. The way the architecture is conceived influences the how well these processes can be conducted. The standard describes generically four categories of processes:

- *Agreement* processes focus on acquisition and supply.
- *Organizational project-enabling* processes support the conduct of projects, and include the management of the lifecycle model, infrastructure, portfolios, human resources, quality, and knowledge.
- *Technical management* processes deal with planning, assessment and control, and the management of decisions, risks, configuration, and information. It also contains processes for measurements and quality assurance.
- *Technical* processes encompass business or mission analysis, and the definition of stakeholder needs and requirements, system architecture, and design. It also covers system analysis, implementation, integration, verification, transition, validation, operation, maintenance, and disposal. It is common that stakeholder concerns exist that related to a broad range of these processes.

A particular concern is often related to some quality of the system to which the architecture applies. Although an architecture is not a complete design, the principles set in the architecture constrains what detailed design choices can be made and hence affects what quality levels are achievable.

The 25010 standard provides a quality model, which contains a set of quality properties. These are broadly characterized as quality in use and product quality. *Quality in use* covers the outcomes of interactions with the system and contains the categories effectiveness, efficiency, satisfaction, freedom from risk, and context coverage. *Product quality* deals with other aspects not directly connected to a user, and includes functional suitability, performance efficiency, compatibility, usability, reliability, security, maintainability, and portability. How well the architecture supports non-operational concerns is often the main discriminator between different alternative solutions, and hence properties across the whole lifecycle need to be considered.

2.3. Systems-of-interest and systems-of-systems

Since an architecture defines concepts, properties, and principles for a particular system, it is essential to be clear about which system this is. The 15288 standard uses the term *system-of-interest* (SoI; see also Section 1.3. above) to clarify that it is an observer who defines the system. Therefore, different observers can have different SoIs. In a larger setting, such as an enterprise, it is common that some stakeholders are only concerned with a subset of the entire system.

In some situations, a system consists of a set of interacting, but largely independent, *constituent systems* (CS), and such a situation is referred to as a *system-of-systems* (SoS). An important characteristic of an SoS is that the CS have a degree of operational and managerial independence, while still contributing to the SoS capabilities. They may also share a common goal or benefit from each other in achieving their own goals. SoS pose particular challenges, which are briefly described in the 15288 standard and elaborated in a further set of standards. The 21839 standard describes how the lifecycle processes of 15288 are affected when the SoI is a CS of an SoS; 21840 details lifecycle process issues when engineering the SoS as a whole; and 21841 provides a basic taxonomy for SoS which includes different subtypes of SoS that differ depending on centrality of control and agreement on objectives.

Beyond the standards, a concept that is often relevant when architecting SoS is the *constellation* (Axelsson, 2019). A constellation is a subset of the CS which actively collaborate in some way. The constellation is thus a substructure of the SoS, but it is temporary and dynamic. New constellations are formed to address changing needs, such as carrying out a certain collaborative task, and are dissolved when the task is completed. Defining which types of constellations are allowed is thus a core part of setting the architecture principles of an SoS, and further questions include the need for supporting *mediators* (Axelsson, 2024) that facilitate the interactions between the CS.

2.4. Application in the project

The best practices encoded in the standards described above provide the basis for the methodology used in this work. However, due to the limited size of the project and the explorative nature of the research, the application of the standards has been tailored so that some aspects are omitted or treated superficially. There is also no ambition to formally comply with the standards. In the rest of this section, some more details are given on the used methodology.

Architecture conceptualization

The system-of-interest (SoI) for this work is specifically the haulage processes within the mine, rather than the entire mining operation, as discussed in Section 1.3. above. These processes encompass the

loading and transport of materials, which are central to the mine's functioning and involve a variety of interacting systems and stakeholders.

Importantly, haulage processes are often isolated and simultaneous, with distinct missions, for example, transporting ore, waste rock, or acid-generating materials, each requiring separate handling and routing. These differing objectives mean that transport can be orchestrated by entirely different vehicle brands, technologies, and operational solutions, running in parallel and sometimes independently of one another. Though these activities occur within the boundaries of the mine and the mine owner retains substantial oversight, haulage frequently includes tasks performed by external contractors who maintain a degree of operational and managerial independence. This arrangement is expected to persist, and possibly expand, with the introduction of autonomous solutions.

As such, the haulage processes are best understood from a system-of-systems (SoS) perspective: they comprise multiple constituent systems, such as mobile machines, equipment, and management platforms, that collaborate while retaining distinct roles and autonomy. The SoS perspective is therefore highly relevant, as it highlights the need for coordination, interoperability, and adaptability amongst diverse actors and technologies, ensuring efficient, safe, and robust haulage operations in a dynamic mining environment.

Within the SoS, constellations are formed to create coordinated workflows, such as a haulage process, but also to ensure safety and efficiency in shared spaces (AOZ), such as where different transport routes intersect (see Use cases in 3.1.).

In the elicitation of architecture alternatives, we have focused on information interoperability across various systems. This includes information exchanges between different mobile machines, but also with IT systems for management and control of the transport processes. This requires description of the key characteristics of each architectural entity, the communication paths between them, and mediators that are needed. The kind of information to be exchanged also needs to be detailed. However, although the focus is on information exchange, different solutions can also have considerable physical implications, such as requiring different autonomous workflows to be physically isolated.

Information about stakeholders and their concerns has been collected through several means, including project workshops, site visits to get an improved contextual understanding, as well as literature. The latter included also emerging technical standards for autonomous machine operations.

The main stakeholder roles in focus are the developers, owners, and operators at the SoS, constellation, and CS level (Svenson & Axelsson, 2022). Note that these roles can be filled by different actors in different architectural solutions, especially at the constellation level (where the constellation operation could be ensured by a CS manufacturer, the mine owner, or a third party).

The most relevant lifecycle phases are the technical ones related to development and operation, but also agreement processes since the mine owner needs to acquire systems and services from various providers.

Architecture elaboration

In the elaboration phase, a selection of views was used. These did not adhere to any prescriptive viewpoints, due to the explorative nature of the investigation. Hence, no architecture framework was used, because of the added complexity of the general frameworks and the lack of more specific frameworks for this sector. Some of the views included:

- Use case description: Different use cases were enlisted and described textually and with informal graphics (see Section 3.1.).
- Stakeholder concerns: These were also enlisted and described textually (see Section 3.3).
- Communication: To clarify message exchanges, sequence diagrams were used (see Section 4.2).

- Architectural principles: A set of principles were identified and described textually (see Section 5.1).
- Functions: A number of functions in the autonomous system stack were identified and clustered into domains (see Section **Fel! Hittar inte referensälla.**). To complement textual descriptions, class diagrams were used.
- Topology: Alternative ways of structuring the overall automated hauling system into subsystems, and their relations and communication channels, were identified and described in text and informal graphics (see Section **Fel! Hittar inte referensälla.**).

Architecture evaluation

The evaluation of architectural alternatives was conducted through a qualitative and exploratory analysis, focusing on a selected set of quality properties representing the most significant concerns affected by different interoperability approaches. Rather than relying on quantitative metrics or prescriptive evaluation frameworks, the project emphasized analytical reasoning grounded in standards analysis, stakeholder dialogue, and practical experience from real mining contexts.

Architectural alternatives were examined in relation to how they influence these quality properties—such as evolvability, responsibility allocation, safety, and interoperability—across system boundaries. Relationships and potential trade-offs between the quality factors were identified and discussed through workshops, expert discussions, and iterative refinement, ensuring that both direct and indirect impacts on operational objectives were considered.

This approach enabled the project team to capture nuanced, practice-oriented insights into interoperability challenges and to support decision-making based on practical priorities, lifecycle considerations, and sector-specific constraints rather than abstract optimization.

3. Haulage automation in mining

Mining operations are inherently complex and dynamic, requiring the careful coordination of multiple material flows within the site. At their core, these operations involve the extraction, transport, and processing of different materials such as ore, waste rock, and potentially acid-generating (PAG) rock, each of which must be handled and routed separately to ensure safety, environmental compliance, and operational efficiency. The movement of these materials is not static; operational priorities can shift, for example, with mines sometimes choosing to prioritize waste transport over ore haulage, particularly when fluctuations in market prices make this a more viable or strategic option. Additionally, extraction sites within the mine are regularly relocated as operations progress. This constant shifting of mining locations requires the logistics network to be continually adapted, ensuring that transportation routes, equipment deployment, and scheduling remain aligned with the changing operational landscape.

The allocation of truck fleets and resources to these distinct material flows is a key factor in achieving production targets and optimizing costs.

Furthermore, mining is a round-the-clock endeavor, typically running 24 hours a day to maximize output and return on investment. This continuous operation adds another layer of complexity, as it requires robust planning, scheduling, and maintenance strategies to ensure that equipment and personnel can sustain such demanding cycles. Overall, the intricate interplay of material flows, shifting priorities, and relentless operational tempo defines the challenging nature of modern mining operations.

Current autonomous systems are restricted to an Autonomous Operating Zone (AOZ), which creates physical barriers and limits operational flexibility. Most suppliers offer closed autonomy stacks, resulting in poor interoperability between machines from different manufacturers. As a result, each AOZ typically supports only one supplier of autonomous machines.

3.1. Use cases

To illustrate the practical objectives of this project, we present an architectural view consisting of a structured set of use case areas. These areas clarify not only the operational goals but also the diverse context in which the proposed systems will be applied. By detailing specific situations and interactions within each use case area, we provide a foundation for further analysis, helping to define requirements and guide the development of interoperable solutions. Rather than aiming to be exhaustive, the use case areas focus on the most relevant operational challenges and typical scenarios encountered in mining automation. This approach ensures that the examples remain realistic and directly applicable to the sector's current needs.

The use case areas described break down the overarching aim of the initiative into tangible, focused components. Through these areas, we capture the key challenges, opportunities, and workflows that are most pressing for successful implementation. Each use case area presents a depiction of operational objectives and outlines the specific environments and settings for introducing new solutions. The focus is on practical processes, typical stakeholder interactions, and essential technical considerations that must be addressed as the project progresses.

For clarity and ease of reference, the use case areas are organized into three principal categories: Operations; Control and Optimization; and Safety and Diagnostics. Each category contains representative scenarios that reflect realistic challenges and solutions, rather than hypothetical or idealized cases.

Operations: This use case area is grounded in actual mining practices and addresses all aspects of autonomous traffic, movement and physical handling of materials. It includes procedures such as

loading, transporting, and unloading ore and waste, and the routine coordination of mobile machines. Realistic scenarios include managing shared loaders, coordinating movements in narrow haul roads, executing maneuvers in open unloading zones, and crossing intersections, situations that mining teams encounter daily, see Figure 3. The emphasis is on how interoperable systems can improve efficiency and safety in these typical operational contexts.

Operations Management: This area focuses on the practical use of real-time fleet data, consolidated to control and optimize scheduling and resource allocation. Examples include adjusting transport plans in response to changing site layouts or ore grades and leveraging geospatial analytics to reroute equipment as needed. The use cases need to be designed to mirror common challenges, such as responding to bottlenecks or unexpected equipment downtime, ensuring that the solutions proposed are relevant and achievable with current technologies.

Safety: This use case area centers on realistic safety protocols and diagnostic routines essential for autonomous and semi-autonomous mining. It includes familiar procedures such as emergency stops, collision avoidance, and equipment shutdowns, as well as the use of monitoring systems for early fault detection and maintenance planning. The scenarios are drawn from industry standards and everyday operational requirements, ensuring that the proposed solutions are both practical and implementable.

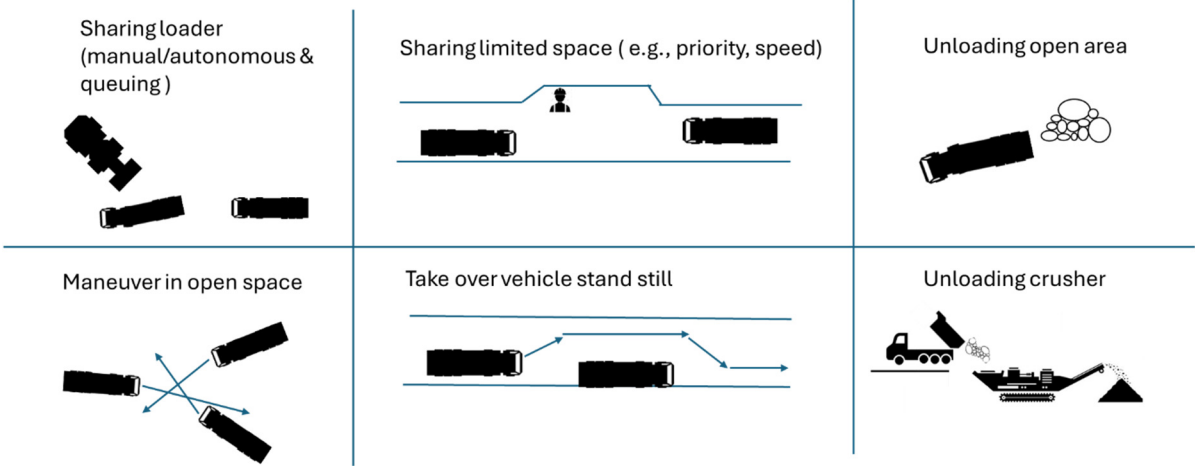


Figure 3 Example use case illustrations

Operations

- **Loading Spotting:** Autonomous haulers/trucks must accurately position themselves under loaders, taking into account variable terrain, loader movements, and ore types. Interoperable systems should enable seamless coordination between loaders and haulers, regardless of manufacturer.
- **Traffic Coordination:** Effective movement of a fleet of autonomous mobile machines across narrow haul roads, intersections, queuing, over takes and other shared zones is critical for safety and efficiency. Interoperable traffic management allows mobile machines from multiple OEMs to navigate shared routes and AOZ without conflict.
- **Integration with Manual Operations:** Ensuring smooth interaction between autonomous and manual mobile machines, including joint traffic coordination, shared loading zones, and safety routines.
- **Unloading:** The process of unloading at designated zones, including open areas and crushers involves precise maneuvering and timing. Interoperable systems can facilitate smooth transitions, coordinate with stationary machinery, support staff, and adapt to changing site layouts.

Operations management

- **Schedule Transport:** Dynamic scheduling adapts to shifts in production priorities, ore grades, and site conditions. Interoperable fleet management systems can integrate multi-brand mobile machines, adjusting schedules in real time to meet operational targets.
- **Dispatch Transport Mission:** Dispatching transport missions involves assigning tasks to available mobile machines based on mission and vehicle characteristics, location, load, and operational status. Interoperable dispatch frameworks ensure all mobile machines, regardless of brand, can be assigned optimally.
- **Transport Mission Optimization:** Continuous optimization of transport missions reduces bottlenecks and improves resource utilization. Interoperable analytics can provide holistic insights and enable flexible rerouting when unexpected downtime occurs.
- **Common Map Synchronization:** Ensuring all autonomous systems operate using an updated, representative, and accurate common map is essential for safe and efficient operations. This use case focuses on real-time synchronization of geospatial information across all mobile machines and control platforms, regardless of manufacturer. When a site layout changes, such as new roads, closed areas, or shifting loading zones, the common map is immediately updated and distributed. As a result, all autonomous mobile machines, loaders, and support equipment adjust their navigation, routing, and operational decisions based on the same information, preventing route conflicts, reducing navigation errors, and enabling coordinated responses to dynamic site conditions.

Safety

- **Emergency Stop:** Emergency stop procedures across all autonomous mobile machines, regardless of manufacturer, are important for preventing accidents and ensuring rapid response to incidents.
- **Monitoring:** Continuous monitoring of vehicle status and operational environment supports early detection of faults, maintenance planning, and situational awareness. Interoperable monitoring systems aggregate data from diverse equipment for comprehensive oversight.
- **Safety Protocols:** Implementing common safety protocols across multi-OEM fleets ensures consistent behavior in hazardous situations, such as collision avoidance and equipment shutdowns.

Use case examples beyond SOI

These use case types may be relevant for further interoperability study but are not included here.

- **Map and Geospatial Analytics:** Real-time mapping and spatial data analytics are essential for planning optimal routes, avoiding hazards, and responding to site changes. Interoperable mapping tools allow integrated decision-making across mixed fleets.
- **Maintenance Coordination:** Automated scheduling and execution of maintenance tasks, integrating diagnostics from all mobile machines and equipment, regardless of brand.
- **Environmental Monitoring:** Real-time integration of environmental sensors and data from autonomous mobile machines to support compliance, sustainability, and site management.
- **Incident Reporting and Response:** Standardized reporting and coordinated response to incidents, leveraging interoperable communication across all autonomous systems.
- **Operator Intervention:** Safe and efficient handover procedures for operators to intervene or override autonomy in mixed-brand fleets.

3.2. The need for interoperability

At present, autonomous technologies are mostly used in specific sub-processes within narrowly defined geographical areas, limiting their overall impact. This restriction not only reduces the potential benefits of automation, but also negatively affects the flexibility and efficiency of mining operations, as other processes may have to expand their range, incur higher costs, or lose productivity to compensate for these limitations. In the SoS terms introduced earlier, the CS mostly operate independently and hence the mining operation does not take full advantage of the possibility to use constellations of CS effectively.

When mines adopt autonomous equipment from a particular vendor, they typically must also implement that vendor's complete automation system, including training personnel and obtaining safety certifications. In the future, a more efficient and competitive strategy would be to pursue interoperable solutions. Such an approach would allow mines to make better use of existing IT investments, simplify licensing, minimize the need for multiple data and control centers, and optimize staff requirements in both IT and operations. Mines would then be free to choose the most suitable autonomous equipment irrespective of manufacturer: constellations could be formed regardless of who manufactures the CS. This interoperability would substantially lower the costs involved in deploying autonomous technologies, especially for those who lead the way, and make it easier to scale up investments. Most importantly, allowing different brands and types of machines to operate together in the same area could greatly speed up deployment, since no single provider is able to supply every piece of equipment needed for effective and scalable (up and down) mining and its supporting operations such as physical infrastructure (e.g. roads, support walls, drainage etc.)

3.3. Concerns with lack of interoperability

Mining companies face significant concerns due to the lack of interoperability between autonomous systems. Today's mixed brand autonomous fleets cannot use a single common dispatch and safety framework. The result is inefficient fleet utilization, costly system integrations, operational silos, and reduced safety margins. This vendor lock-in increases lifecycle costs and limits the mine's ability to scale, adopt best-in-class technology, and innovate. All these factors are examples of evaluation criteria for the architecture.

Mines often shift priorities, maximizing ore production when prices are high and focusing on waste removal or support activities when prices drop. Therefore, fleet utilization is adjusted according to varying transport needs and several other factors. At present, mines are not able to operate autonomous systems with the same flexibility as manual machinery.

Interoperability between multi-OEM AMS and the FMS can improve safety, efficiency, cost effectiveness, and flexibility. However, most systems still run in isolation with little integration.

The seven pain points from lack of interoperability of AMS can be described as:

Operational Silos

- AOZ often exclusively occupies (locks) specific areas of the mine requiring costly rearrangements and possible inefficiencies due to non-optimal routes and operations of the entire mine.
- Dispatch systems, safety controls, and maintenance planning do not communicate across OEM platforms.
- Creates parallel workflows for operators and workers, reducing efficiency.
- Recruiting and training separate teams for each system is also costly and time-consuming

Vendor Lock-In

- Mines often need to buy entire fleets from a single OEM to ensure compatibility
- Limits bargaining power and increases lifecycle costs.
- Reduces flexibility to adopt best-in-class solutions from different vendors.

Integration Costs and Complexity

- Each OEM provides its own proprietary control, monitoring, and data formats.
- Mining companies must build and maintain costly custom integrations including specific Infrastructure (IT), data centers and related licenses.
- Slows down deployment of new equipment or software.

Inefficient Fleet Utilization

- Haulers from different OEMs cannot run in the same dispatch system.
- Makes it harder to scale or redeploy assets across sites and zones.
- Moving a loader between autonomous operating zones takes time and often needs major reconfiguration.
- Loaders cannot be shared across AHS without re-installation and re-configuration. This causes under-use of equipment when part of the fleet is down.

Safety and Reliability

- The absence of standardized protocols, communication channels, and emergency control measures increases the likelihood of mistakes occurring due to human error. This not only poses a significant risk when operating multiple AOZs on the same site, but it can also prevent the implementation of mixed AMS traffic altogether.
- Risks in coordination during critical operations (e.g., collision avoidance, traffic management).

Limited Innovation and Digitalization

- Fragmented data makes it harder to use analytics, AI, and optimization tools.
- Costly to create local integrations and leverage local innovation.
- Slows progress toward autonomous, fully integrated mine operations.

Higher Total Cost of Ownership

- Resale value can drop if equipment only works within one ecosystem.
- Mines pay more for spare parts, training, and vendor-specific support.

4. Current state and external analysis

The development and deployment of autonomous systems in industrial environments have progressed rapidly in recent years, transforming operational practices and driving efficiency gains. This chapter provides an overview of the current state of the art, highlighting advanced technologies implementations and use at real mining sites, relevant industry standards and ongoing initiatives. The main method has been to examine integrations of different solutions from various manufacturers at pioneering mining sites. This is complemented by reviews of important standards and the research literature. In terms of defining the future architecture, these inputs provide examples and patterns that can be evaluated as potential alternatives.

4.1. Boliden site operations

Komatsu

The project team visited the Aitik mine, where Boliden operates a dedicated Autonomous Operating Zone (AOZ), specifically for the Komatsu autonomous haulage system known as FrontRunner AHS. The AOZ is restricted from general traffic and from other production flows within the mine. It is a remote area located close to the main mine site, which continues to be manually operated. Manually operated machines, such as wheel loaders, motor graders, and passenger cars, may coexist within the AOZ, provided they are fitted with dedicated and proprietary equipment and their operators are trained and certified for the area. At present, only certain Komatsu machines are permitted to operate autonomously within the AOZ. Older Komatsu models and those from other manufacturers are not compatible with autonomous operation in this zone.

The operation makes use of dedicated loading and unloading areas as well as specialized machinery. Purpose-built infrastructure has been installed, including wireless communication, localization systems, mapping platforms, and a central command center (FMS). Manually operated mobile machines are permitted within the AOZ but must incorporate proprietary technology to ensure safe integration with the autonomous infrastructure. Furthermore, all personnel operating or entering the AOZ must complete specialized training to guarantee safe interaction within this advanced environment. Robust cybersecurity and data integrity measures are in place to safeguard communications and operational data; this includes the deployment of dedicated data centers and segregated networks.

The autonomous operation at Aitik runs continuously, 24 hours a day, 365 days a year. The fleet consists of 17 trucks, with 12 in simultaneous use during the visit. Each truck has a weight of approximately 291 tonnes and can carry a load of around 300 tonnes, resulting in a total vehicle weight of nearly 600 tonnes when fully loaded. The maximum permitted operational speed for the trucks is 50 km/h, and the driving range is 3 km one way from loading to unloading.

Several benefits have been observed and reported as a result of the autonomous system:

- Maximized use of available operating hours, keeping the fleet productive throughout the schedule.
- Elimination of disruptions caused by human operators, as autonomous systems are unaffected by factors like fatigue or distraction.
- Trucks consistently follow optimal routes within the designated operational area, avoiding unnecessary detours.
- Fewer trucks are needed to perform the same workload, thanks to improved efficiency and reduced downtime.

- Consistent driving behaviour, with autonomous mobile machines operating identically each cycle, enhancing predictability and safety.
- Reduction in cascading damage, as autonomous systems prevent chain-reaction incidents typically caused by human error.
- Prevention of incorrect equipment usage, which helps prolong machinery lifespan and ensures adherence to operational protocols.

Compared to traditional mining operations, new roles such as pit patrols and control center personnel have been introduced. Three pit patrols are on duty simultaneously, serving as eyes on the ground, able to shut down operations, provide physical support, enable or disengage trucks, and establish routes and boundaries for the mobile machines. The control center is responsible for numerous tasks, utilizing several independent systems to manage safety and operational boundaries, monitor the autonomous system, and oversee the FMS, including truck dispatch. Additionally, expanded training programs and an increased number of maintenance technicians are now part of the operation.

Sandvik

Another site visit was conducted at the Garpenberg mine, where Boliden has an autonomous and remotely operated Load -Haul-Dump (LHD) operation as part of their underground mining operations. The LHD machine performs mucking at the face, transporting the broken rock from the heading and dumping it into an ore pass for intermediate storage. This setup does not utilize a Fleet Management System (FMS), allowing for a streamlined approach tailored to the specific needs of the operation. Currently, one machine operates within each AOZ at a time, ensuring clear separation and minimizing the risk of incidents. Each AOZ is controlled by physical sensors which monitor and guarantee that no unauthorized machines or personnel enter the area, thereby maintaining strict safety protocols.

Material transport and unloading operations are fully autonomous, contributing to efficient and predictable workflows.

Loading operations are performed remotely by human operators, with each loader seamlessly switching between remote-controlled and autonomous modes for every load cycle. Specific maneuvers such as loading were still performed better by remote control than autonomously.

The IT environment supporting these operations is a hybrid model, leveraging both cloud-based and on-premises infrastructure to ensure reliability and scalability.

This configuration highlights a careful balance between automation and human oversight, with robust safety measures and adaptable operational models supporting Boliden's underground mining activities at Garpenberg.

The following benefits were observed or reported by the mine staff:

- Increased safety as there are no human in the drifts,
- The operators are less exposed to noisy, vibrating and polluted air working conditions.
- Productivity increase as operators can operate several LHD:s simultaneously.
- Reduction in cascading damage, as autonomous systems prevent chain-reaction incidents typically caused by human error.

Volvo Autonomous Solutions

The site visit at Boliden's Garpenberg mine also studied a dedicated AOZ used for dam construction. The purpose is to take crushed stone material from one side to the other where the dam wall enforcement construction is built. It is a dedicated closed area without crossings of other machinery or vehicles. There are manual machines in the area which consist of a wheel loader loading the trucks and a dozer at the unloading area managing spotting of unloading and material handling. The machines for loading and

unloading are equipped with dedicated and proprietary equipment for managing its tasks. Dedicated infrastructure has been installed for wireless communication, localization, mapping platforms and central command, safety and fleet management (FMS) systems.

4.2. Related standards

This chapter provides an overview of the relevant standards that underpin the deployment and safe operation of autonomous and semi-autonomous machine systems in mining environments. It highlights key aspects of interoperability and safety, drawing attention to both what is currently addressed in international standards and where notable gaps remain. The following sections summarize the main standards and their implications for practical implementation in real-world scenarios.

ISO 23725:2024 - Autonomous system and fleet management system interoperability

ISO 23725:2024 addresses interoperability between autonomous hauler systems (AHS) and fleet management systems (FMS), enabling different suppliers for each. ISO 23725:2024 has an intended scope of open pit mining. The standard defines how messages and activities are exchanged between an AHS/virtual driver function and an FMS (see Figure 4 and Figure 5). Note that ISO 23725 does not cover execution-phase messages shown in Figure 5, but it does define assignment category messages.

In this report, ISO 23725 serves as a foundation for discussing current solutions and identifying key challenges related to coordination and safety in autonomous mining environments.

ISO 23725 is a highly relevant standard for interoperability for automated machines in mining environments. However, the standard does not address all needs for achieving interoperability, particularly during the execution phase, where clear guidelines for practical collaboration between machines from different OEMs are missing. To facilitate interoperability during execution, there is a need for more detailed mechanisms for information exchange and interoperability protocols, especially in multi-AHS environments where several independent systems must work together. Thus, while the standard provides an important basis, it leaves many practical and technical questions unanswered, issues which the report further examines through examples and case studies.

ISO 17757:2019 - Autonomous and semi-autonomous machine system safety

ISO 17757:2019 – Autonomous and semi-autonomous machine system safety is primarily concerned with the general safety requirements for autonomous and semi-autonomous machinery used in mining and similar environments. In this context, the term AOZ refers to the Autonomous Operating Zone, which is a designated area within a mine where autonomous or semi-autonomous machines are permitted to function independently. The standard also addresses specific safety requirements such as the implementation of remote stop functions, ensuring that operators or supervisors can halt machine operations from a distance in case of emergencies or unsafe conditions. These requirements are critical for maintaining safety in environments where human workers and autonomous machines may interact.

Unlike ISO 23725:2024, ISO 17757 does not address interoperability or define specific protocols for communication between different systems or machines from various OEMs. Instead, its focus is on establishing safety principles and guidelines that ensure such machines operate without posing undue risks to people, property, or the environment. As such, while it plays a crucial role in the safe deployment of autonomous machinery, it does not directly contribute to solving challenges related to interoperability or collaborative operation between systems from different suppliers.

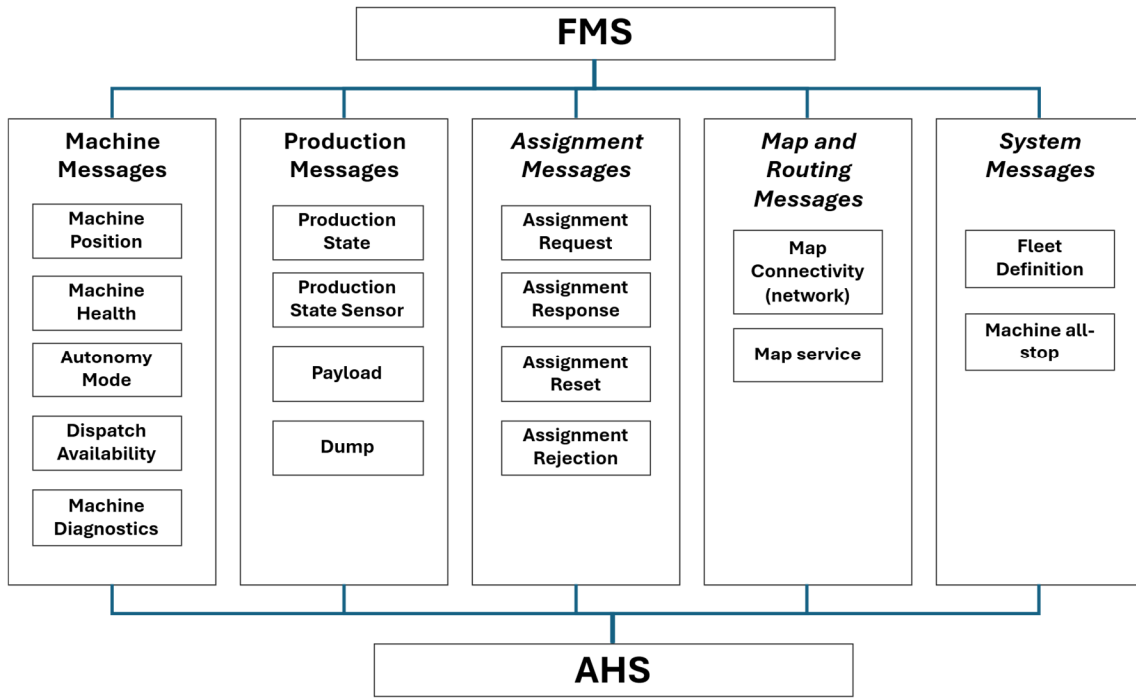


Figure 4 ISO 23725 defined message types and categories

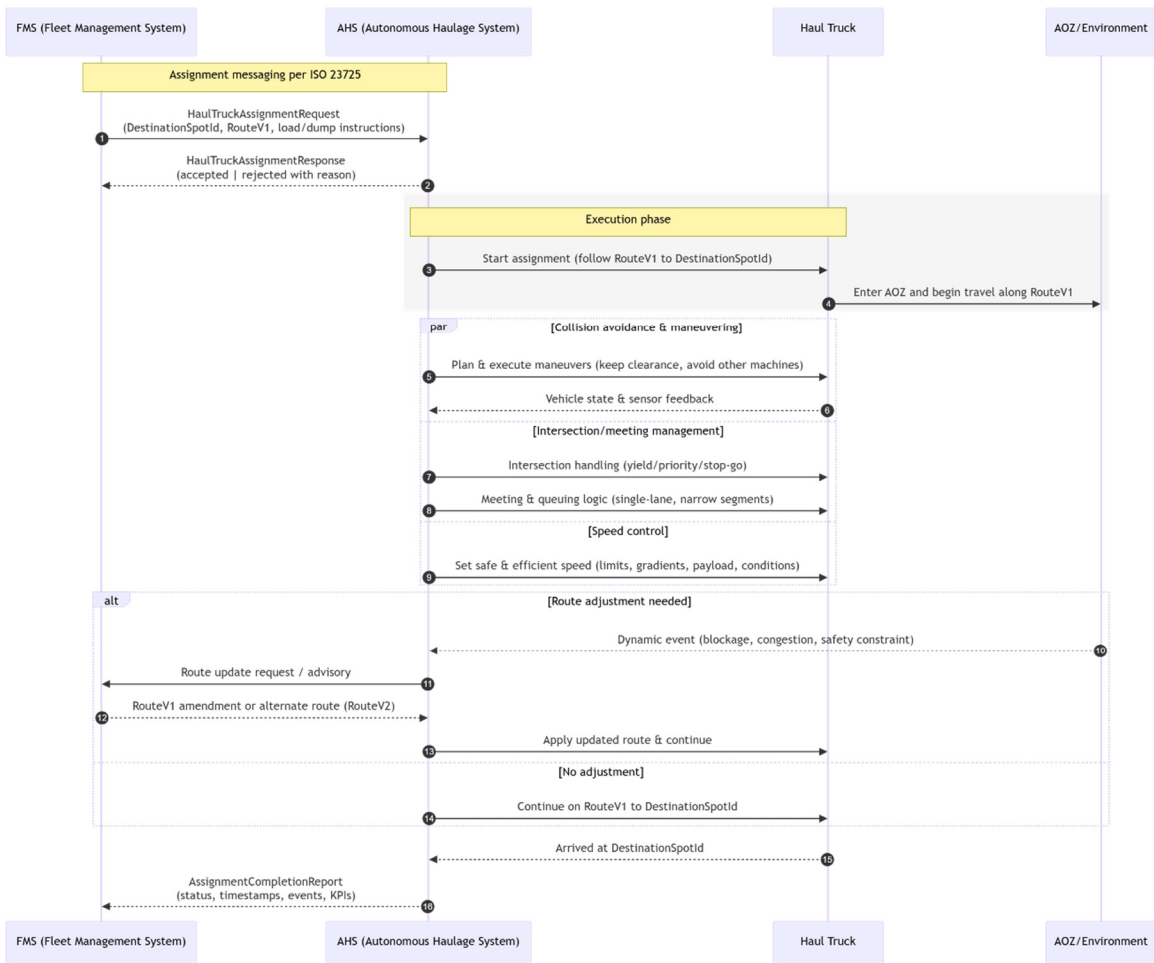


Figure 5: Example of messages and activities according to ISO 23725 and our proposed Class structure. Execution phase highlight concept message types beyond ISO 23725.

4.3. Literature on autonomous machine systems

Research into autonomous haulage and collaborative autonomous systems within mining has grown considerably in the past decade, mirroring the sector's ongoing transition towards safer, more efficient, and increasingly interoperable operations. Voronov, Voronov, and Makhambayev (2020) provide an extensive review of the current landscape and development trends for autonomous haulage in surface mining, noting that the majority of commercial AMS deployments are still proprietary and vertically integrated within individual OEM ecosystems. This observation highlights a central challenge discussed in this report: limited interoperability and the absence of standardized mechanisms for coordinating multi-brand fleets, particularly when such fleets operate together in shared production zones.

A further research strand addresses semantic interoperability and harmonized machine-to-machine communication. Zager, Sieber, and Fay (2024) introduce an information model for autonomous mobile robots that enables consistent data representation across diverse robotic systems. Although not mining-specific, their findings emphasize the value of shared semantics and well-defined information interfaces, principles closely aligned with the intent-based coordination concept advocated in this report, where minimal yet unambiguous data exchange underpins safe interaction between mixed fleets.

Looking more broadly at autonomy in mining, Ruiz-del-Solar (2025) explores progress towards fully autonomous and collaborative mining ecosystems, including dynamic operational zones where autonomous and manually operated machines must coexist safely. His work underscores the industry's shift towards a system-of-systems approach, requiring independent subsystems to coordinate within shared, safety-critical environments. This emphasizes the necessity for scalable coordination mechanisms that can handle heterogeneous actors, emergent behaviors, and evolving site layouts, core motivations for the broker-based coordination architecture outlined in this report.

In addition, the paper by Long, Schafrik, Kolapo, Agioutantis, and Sottile (2024) provides a broad overview of automation technologies and their integration within mining operations. It details the evolution of equipment automation, operational challenges, and the gradual adoption of interoperable systems. The review reinforces the need for pragmatic solutions that bridge the gap between proprietary technologies and open, collaborative frameworks, highlighting the ongoing efforts and remaining barriers to achieving seamless multi-vendor interoperability in mining environments.

To handle operational data sharing in a construction SoS, Axelsson (2019) proposes the use of so-called linked data to represent structure and complex information. This approach, which is based on standards developed for the semantic web, makes it possible to give meaning to data by constructing ontologies to which individual data items are linked. In this way, a powerful and flexible mechanism is provided to give semantics to data. Axelsson (2020) extends this to discuss different levels of interoperability based on linked data, which goes beyond syntax and semantics to also handle pragmatic, dynamic, and conceptual interoperability. These issues are central when addressing complex collaborative operations where the situation awareness of other systems need to be understood.

Collectively, the literature points towards a clear trend for more open, collaborative, and semantically aligned autonomous mining systems. Yet, there is still a gap in practical, deployable architectures that enable safe and scalable coordination of mixed-brand AMS fleets within confined AOZs. This report aims to address this gap by combining system-of-systems principles, model-based engineering artefacts, and a neutral coordination service that maintains OEM autonomy while improving safety and interoperability in real-world mining operations.

4.4. Terminology and concepts in literature

The terminology surrounding Autonomous Haulage Systems (AHS) is critical for ensuring clear communication and effective collaboration within the mining industry, particularly as operations move towards greater automation and interoperability. This chapter introduces and discusses key terms and concepts used in the context of AHS, drawing on relevant standards and literature to promote a shared understanding among stakeholders.

Autonomous Haulage System (AHS)

An Autonomous Haulage System (AHS) comprises integrated technologies designed to enable haul trucks to operate independently within mining environments. These systems typically include virtual driver software, vehicle control, sensors, and communication tools, enabling navigation and material transport without human input. AHS solutions often link with Fleet Management Systems (FMS) for coordinating logistics. There is currently no concise, universally accepted glossary definition of AHS across standards and industry literature. Secondly, the terminology used when referring to AHS tends to exclude other mobile machinery types relevant for automation. ISO 23725 references AHS roles and interfaces but lacks a formal description, while industry groups such as the Global Mining Guidelines Group (GMG) define AHS as “Autonomous haulage systems (AHS) are conventional haul trucks outfitted with OEM-provided operational technology that allows for safe unmanned operation” (Global Mining Guidelines Group, 2022). This definition primarily reflects OEM-integrated solutions and does not explicitly address retrofit-based autonomy. The report’s definition takes into account both ISO 23725 and GMG perspectives. To address these gaps, a broader definition of Autonomous Machine System is introduced in Section 1.7.

Autonomous Machine Systems (AMS) as a conceptual abstraction

A recurring limitation in both standards and literature is the lack of a machine-type-generic term for autonomy in mining. While Autonomous Haulage Systems (AHS) are well established for haul trucks, other autonomous mobile machines, such as loaders, excavators, and auxiliary equipment, are typically described in an ad hoc manner or grouped under broader notions of “autonomous systems in mining” (Global Mining Guidelines Group, 2024). Neither ISO 23725 nor GMG defines a unifying system concept that abstracts autonomy across machine types. To support a system-of-systems analysis and to avoid overloading the AHS concept beyond haulage, this report introduces the term Autonomous Machine System (AMS) as a conceptual and analytical abstraction. AMS is used to denote the autonomous control system associated with a specific type of mobile machine, independent of machine category or supplier. The term is not intended to represent a formally standardized industry concept, but rather to provide a consistent vocabulary for analyzing interoperability, responsibility allocation, and architectural patterns across heterogeneous autonomous machines.

Fleet Management System (FMS)

The Fleet Management System is a supervisory platform responsible for coordinating the activities of all vehicles and equipment within the mine. The FMS assigns tasks (sometimes referred to as missions, assignments, or jobs), tracks vehicle locations, monitors performance, and manages traffic and safety protocols. In interoperable settings, the FMS may communicate with multiple AMSs from different suppliers, where responsibility for task decomposition and execution may be shared between systems, as left open by ISO 23725:2024, and therefore requiring further standardized message formats and protocols for interoperability.

Assignment, mission, and task

The terminology associated with operational directives requires careful consideration. According to ISO 23725, the term assignment refers to a specific type of message transmitted between the FMS and AHS, detailing the activities designated for autonomous mobile machines. Nonetheless, there is inconsistency within the literature regarding the equivalence and distinction among assignment, mission, and task. Irrespective of the terminology selected, it remains crucial to explicitly define its usage in each context to mitigate ambiguity.

Autonomous Operating Zone (AOZ)

The Autonomous Operating Zone is a designated area within a mine where autonomous or semi-autonomous machines are permitted to function independently. Safety requirements for AOZs are governed by standards such as ISO 17757:2019, which mandates features like remote stop functions to ensure that operations can be halted immediately in case of emergencies. AOZs are central to site layout and operational planning, serving as boundaries for autonomous system activities and interaction with manually operated equipment.

5. Architecture strategy and principles

In this chapter, we present the architectural outcomes and insights derived from the project as a whole. We examine how key architectural choices shape the broader design, integration, and operation of autonomous mining systems. By discussing central principles and illustrating with practical examples, including, but not limited to, traffic control, we demonstrate how different architectural patterns impact interoperability, scalability, and collaboration between machines from multiple manufacturers. Our approach is to emphasize the most significant architectural challenges and opportunities identified during the project, providing a clear and comprehensive overview of the strategies and lessons learned that underpin robust, safe, and future-proof autonomous mining environments.

5.1. Architectural principles

The following architectural principles capture the key insights derived from the project. They are intended to guide the design, implementation, and evolution of interoperable autonomous mining systems, particularly in multi-OEM and system-of-systems contexts. Each principle addresses specific operational challenges and quality concerns observed in real mining environments.

Traceable and accountability-driven diagnostics

Autonomous mining operations are safety-critical, geographically distributed, and involve multiple suppliers. Physical access to mobile machines is often limited, making rapid remote troubleshooting essential. At the same time, clear responsibility for faults is required for liability, maintenance, and operational continuity.

Principle: The system architecture shall enable unambiguous traceability from an observed fault to the responsible component, software module, and supplier through standardized logging and diagnostic interfaces.

Intended effect: This principle supports fast troubleshooting, reduced mean time to repair (MTTR), clear accountability across suppliers, and improved management of operational risk and liability.

Modular and layered architecture

Autonomous mining systems are developed, deployed, and upgraded over long lifecycles by multiple organizations. Interoperability increases overall system complexity, which must be actively managed to avoid reduced maintainability and understanding.

Principle: The architecture shall be divided into clearly defined layers and modules with well-defined responsibilities and minimal dependencies. Separation of concerns shall be used deliberately to manage complexity.

Intended effect: A modular and layered structure reduces complexity, enables incremental upgrades, and supports scalable and maintainable system evolution.

Standardized and contract-based interfaces

Multi-vendor integration and the need for early testing, simulation, and validation place strong demands on predictable and well-defined interfaces. Proprietary or undocumented interfaces limit flexibility and hinder interoperability.

Principle: All communication between systems shall occur through version-controlled, documented, and testable interface contracts, such as APIs and data schemas. These contracts shall support integration, simulation, and verification across suppliers.

Intended effect: This principle enables interoperability, reduces vendor lock-in, and lowers integration effort and risk during deployment and evolution.

Safety by design and separation of safety functions

Autonomous mobile machines operate in close proximity to humans and heavy equipment. Failures can have severe consequences, making safety a primary architectural concern rather than an implementation detail.

Principle: Safety-critical functions shall be architecturally separated and prioritized over other functional objectives. The system design shall support compliance with functional safety requirements throughout the entire lifecycle.

Intended effect: This principle reduces risk, supports regulatory compliance, and ensures robust protection of human operators and operational assets.

Evolvability and scalability

Autonomous technologies, AI models, and operational requirements evolve rapidly. Long-lived mining systems must therefore avoid architectural lock-in and support change without large-scale redesign.

Principle: System components shall be replaceable or upgradeable without major redesign of the overall system. The architecture shall anticipate future requirements and support both functional and capacity-driven expansion.

Intended effect: This enables future-proof solutions, reduces lifecycle costs, and supports long-term adaptability of autonomous mining operations.

Balancing scalability, flexibility, robustness, and quality

In interoperable systems, increased openness and flexibility often introduce trade-offs with robustness, reliability, and quality. These trade-offs become more pronounced as systems scale.

Principle: Architectural decisions shall be made with explicit consideration of trade-offs between scalability, flexibility, robustness, and quality, addressing both current and future operational needs.

Intended effect: This supports informed decision-making and helps achieve an appropriate balance between adaptability and dependable performance.

Managing Increased Complexity Through Interoperability

While interoperability enables flexibility and vendor independence, it also increases architectural and operational complexity, which can negatively impact maintainability and reliability if left unmanaged.

Principle: The architecture shall include explicit strategies for complexity management, such as modularization, abstraction, and clearly defined responsibility boundaries between systems and actors.

Intended effect: This principle supports maintainable, understandable systems that remain operationally efficient despite increased interoperability.

Manufacturing cost versus product lifecycle cost

System value depends on both manufacturing efficiency and operational lifecycle cost. Optimizing one at the expense of the other can reduce overall viability and adoption.

Principle: System designs shall optimize both manufacturing processes and product lifecycle costs, maximizing value for suppliers and end users.

Intended effect: This enhances market viability, competitiveness, and user satisfaction.

System lifecycle considerations

Autonomous mining systems must be managed across their entire lifecycle, from design and deployment to operation, maintenance, and decommissioning.

5.2. Strategic paths towards interoperability

This report highlights that mining systems and equipment generally lack interoperability. Proprietary technologies and closed interfaces limit mine operators, making it difficult, expensive, or sometimes impossible to integrate products from different manufacturers. As a result, operators face inefficiency, have less flexibility, and are often tied to specific vendors, which restricts their ability to choose solutions best suited to their needs.

To address these challenges and pursue a wider vision, we have identified four unique approaches to achieve interoperability and create value. Each strategy stands on its own and can be developed and applied separately and independently. The four strategic paths are:

FMS Interoperability

Fleet Management System (FMS) interoperability refers to the ability of different FMS platforms to exchange data and operate collectively within a mine. Achieving FMS interoperability enables mine operators to combine software solutions from various vendors, facilitating centralized monitoring, reporting, and optimization across mixed fleets. This path minimizes costs for IT, such as data centers, networks and SW licenses. It also reduces costs for IT personnel, training and management personnel in case of multiple brand fleet operations at sites. This path focuses on standardizing data protocols and interface specifications, so that production, maintenance, and operational data can be shared seamlessly, ensuring a holistic view of mining operations and more effective decision-making.

AMS interoperability with manual machines

Autonomous Machine System (AMS) with manual machine interoperability is about enabling autonomous systems from different manufacturers to operate together with manual operated machines. This path aims to break down the barriers posed by proprietary AMS/AHS platforms, allowing autonomous mobile machines to share key operational data and coordinate safely on shared spaces with manual machines. This path address the efficiency of operation so that roads and areas can be shared simultaneously and efficiently between support machines, such as road scrapers, dust removal machines/water trucks without disturbing production machines. It also enables certain operational machines such as loaders to be able to feed different haul truck fleets. Standardizing communication protocols and safety requirements is vital, as it promotes efficient mixed-fleet operations and reduces the risk of vendor lock-in, ultimately driving innovation and flexibility in autonomous mining.

AOZ interoperability

Autonomous Operating Zone (AOZ) interoperability focuses on the seamless coordination of equipment and systems operating within designated autonomous zones of a mine. This path involves harmonizing the control, safety, and data exchange standards between various autonomous machines, such as drills, loaders, and haul trucks, regardless of their manufacturer. AOZ interoperability ensures that the entire autonomous zone functions as an integrated ecosystem, supporting safe, efficient, and synchronized operations while allowing operators to select best-in-class solutions for each task. In practice AOZ interoperability means that autonomous system from different manufacturers can co-exist and co-operate to solve physical traffic and operational (such as loading) situations. This enable flexibility to share geographical space and roads to maximize flexibility and productivity in mining operations using the best for purpose autonomous machines independently of brand.

Machine interoperability to external AMS

This path addresses the integration of individual mining machines (such as excavators, drills, or auxiliary vehicles) with external Autonomous Haulage Systems, regardless of brand or origin. The goal is to enable machines to communicate and interact with AMS platforms not originally designed for them, through standardized interfaces and shared safety protocols. Such machine-to-AMS interoperability supports flexible fleet composition, maximizes equipment utilization, and future-proofs investments by ensuring that new or legacy machines can participate in the evolving autonomous haulage ecosystem.

Vision for the future

In the envisioned future, when all four strategies are implemented, interoperability is fully achieved across the mining industry. Mine operators can freely select and combine machines, software platforms, and services based on their operational preferences and strategic goals. Equipment from different manufacturers works together seamlessly, driven by open standards and collaborative industry practices. This flexibility empowers operators to optimize productivity and safety, foster innovation, and respond rapidly to emerging challenges, ultimately ensuring a more efficient, competitive, and sustainable mining sector.

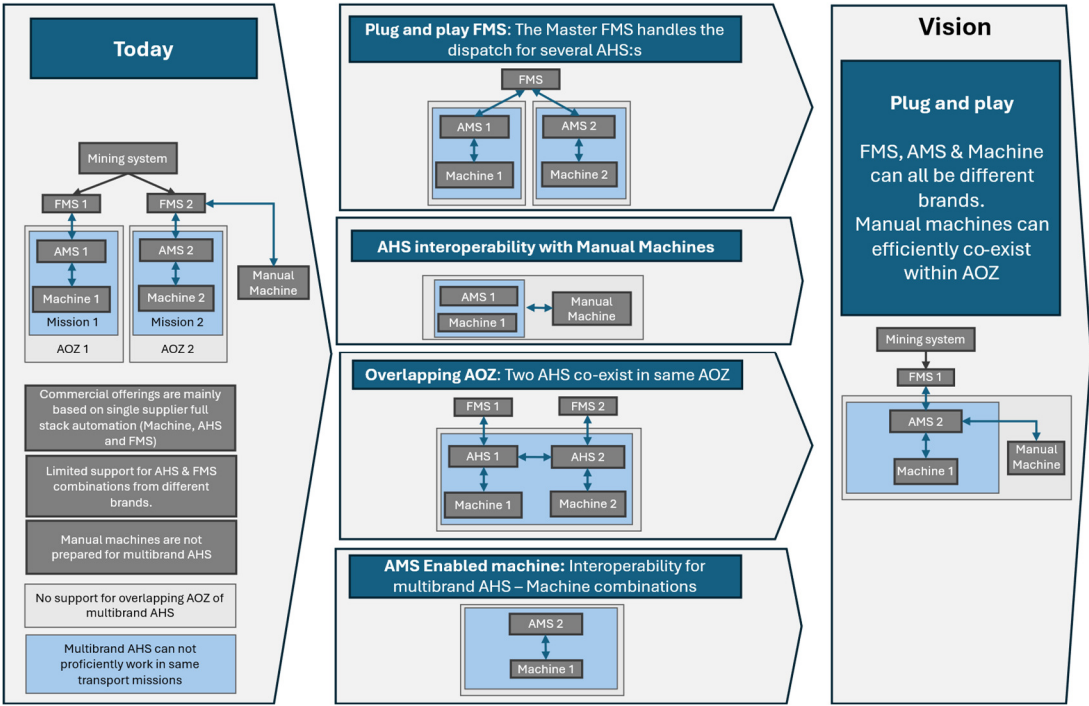


Figure 6 Illustration of strategic paths

5.3. Architectural patterns for traffic coordination in autonomous mining

In the context of autonomous mining, coordinating machines from different Original Equipment Manufacturers (OEMs) within shared physical spaces (AOZ) is of immense value. This section introduces the core principles underpinning traffic coordination in such environments and explains how machines from various manufacturers can effectively collaborate in dynamic workspaces.

The section is structured as follows, providing a overview of both the challenges and solutions for dynamic coordination in autonomous mining zones:

- **Introduction to Traffic Coordination:** Explains the importance of interoperability between systems and machines for productivity and safety in autonomous zones.
- **Key Requirements for Effective Coordination:** Outlines the essential functions and characteristics needed for machines from different OEMs to interact safely and flexibly, including situation awareness, context understanding, and dynamic risk assessment.
- **Information Exchange as Foundation:** Describes the types of information that must be shared between machines and systems to enable smooth and safe coordination.
- **Architectural Patterns:** Discusses different models for communication and collaboration between machines, centralized, federated/brokered, and peer-to-peer (decentralized), and their impact on information exchange and decision-making.

Together, these parts form a logical structure, where each segment builds upon the previous one. The aim is to give the reader a comprehensive understanding of how interoperability and traffic coordination can be practically implemented, regardless of manufacturer.

Why traffic coordination matters

As autonomous mobile machines operate in close proximity, particularly at intersections, single-lane areas, narrow road segments, or other conflict zones—ensuring safe and efficient coordination is vital for both operational safety and productivity. Static, rule-based approaches (such as traditional traffic lights or right-of-way protocols) may suffice in simple scenarios but are inadequate for the complex and variable environments of modern mines.

Dynamic coordination systems allow machines from different manufacturers to adapt to real-time information about vehicle locations, operational status, and hazards. This flexibility leads to continuous optimization of traffic flow, improved safety, and maximize productivity.

Key requirements for effective coordination

- **Situation Awareness:** Machines must perceive elements in the environment, understand their meaning, and predict their status in the near future (Endsley & Jones, 1997).
- **Context Understanding:** Interpretation of map geometry, adherence to traffic rules, application of priority logic, and sharing operational intent (e.g., “turn left at the next crossing”).
- **Dynamic Assessment:** Continuous evaluation of collision risks, speed profiles, data accuracy, avoidance of unintended stops, and maintenance of smooth operational flow.

Information exchange: foundation for coordination

To achieve seamless traffic coordination, systems must exchange critical information, including:

- **Cartography:** Shared digital maps defining crossings, open areas, and lane widths.
- **Machine Characteristics:** Real-time data on position, speed, and size.

- **Operational Status:** Information on process state (e.g., loaded/unloaded), material type, and assigned priority.

At the heart of traffic coordination architecture lies a decision-making layer, which applies operational rules and intent to resolve conflicts among machines. Coordination channels surrounding this layer enable interoperability and negotiation between systems from different OEMs, supporting safety, fairness, and productivity in mixed-fleet environments.

Architectural Patterns for Traffic Coordination

To address the information exchange for traffic coordination, three principal architectural patterns are identified, each with distinct approaches to control and data exchange:

Centralized Coordination: A single master system makes all traffic and intersection decisions. Suitable for mines operated by a single entity with a homogeneous fleet, offering clear authority but introducing a single point of failure and potential latency issues. **Pros:** This approach offers clear authority and simplified decision logic, making it suitable for mines operated by a single entity with a homogeneous fleet. **Cons:** However, the model introduces a single point of failure and potential latency issues if the master becomes overloaded or disconnected. The master must have a complete view of the entire operation and AOZ.

Federated/Brokered Coordination: Each OEM's central system manages its fleet, with a broker mediating traffic decision. Preserves OEM autonomy and allows flexible integration, but requires standardized interfaces and more complex logic. **Pros:** This preserves OEM autonomy and allows for flexible integration of multiple fleets. It allow for distributed Safety protocols for each OEM fleet. There does not need to be a complete view of all fleets at one point. **Cons:** This approach demands a standardized interface and involves more complex logic than a centrally coordinated system, which may introduce latency risks if broker communication is delayed. However, using multiple brokers for different regions allows for greater flexibility. A federated solution is generally considered more robust than a centralized one, as it eliminates reliance on a single point of failure.

Peer-to-Peer (Decentralized) Coordination: Machines negotiate directly using local protocols. This approach eliminates central dependencies and can reduce latency, making it well-suited for highly dynamic environments with frequent fleet changes. Without a central authority, ensuring all machines are aligned on operational protocols and safety measures can become increasingly difficult, potentially leading to coordination bottlenecks or inconsistencies in large-scale deployments. **Pros:** While this model reduces latency and avoids central points of failure, its scalability may be limited by the challenges of managing distributed consensus and ensuring reliable communication across a large fleet. Therefore, peer-to-peer coordination is most effective in smaller or moderately sized operations where direct negotiation is practical and manageable. **Cons:** Ensuring consistent safety, fairness, and rule updates can be challenging, especially as fleets evolve or operational requirements change. Likely need a supervisor ensuring versioning and updates of all fleets.

Each model has its advantages and disadvantages, and the choice depends on operational scale, fleet composition, and integration requirements.

Summary

This revised structure reduces repetition and clarifies the flow of information, helping the reader understand the practical aspects of interoperability and traffic coordination in autonomous mining. Each section logically builds on the previous, guiding the reader from the importance of coordination, through requirements and information exchange, to architectural alternatives and their respective trade-offs.

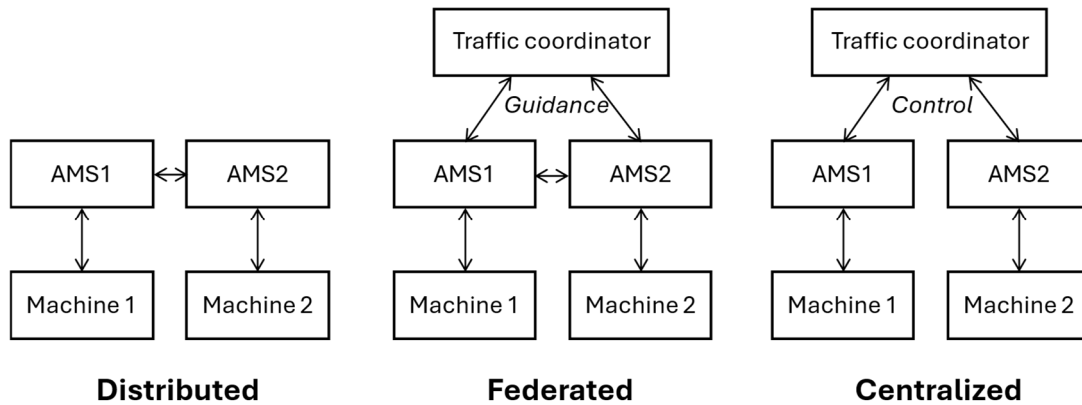


Figure 7 Architecture patterns for traffic coordination

Trade-offs and future directions

The choice of architectural pattern for traffic coordination of in autonomous mining is influenced by operational scale, fleet composition, and integration requirements. Centralized models offer simplicity but risk single-point failures, federated approaches balance autonomy with interoperability, and decentralized systems provide maximum flexibility at the cost of increased complexity. A more detailed study is needed to further evaluate these patterns, especially as industry standards and interoperability protocols continue to evolve.

5.4. Verifying and validating interoperability

Testing and validation methods for interoperability of autonomous machines are essential to ensure seamless integration and reliable operation across various platforms and environments.

For the autonomous mine, interoperability goes beyond ensuring that mobile machines from different manufacturers can connect to each other. Here, interoperability is a means to enable coordinated action in a shared operational context, not a goal in itself. Thus, it cannot be validated by testing of isolated interfaces, one on one. What must be tested is the ability of a constellation of constituent systems to safely and efficiently perform a use case together.

Simply transferring and interpreting data between systems is not sufficient for reliable interoperability, especially in complex environments like autonomous mining. While successful data transfer ensures that messages reach their destination, and interpretation confirms that the receiving system can process the information according to predefined protocols, true interoperability requires semantic understanding. Semantic understanding means that each system not only receives and interprets data, but also comprehends its meaning in the context of the current operation or use case. This is crucial because different constituent systems may have diverse roles, behaviors, and expectations. Without semantic alignment, systems might misinterpret the intent behind the data, leading to errors, inefficiencies, or even safety risks. For example, a vehicle might receive a command to stop, but if it does not understand why or under what circumstances, it may not respond appropriately. Therefore, validation must ensure that the constellation of constituent systems can safely and efficiently perform a use case together, which includes verifying that all participants share a common, contextual understanding of the exchanged information.

Another consequence of the system of systems view of autonomous mines is that not all actors may need to be interoperable with all others all the time. Interoperability becomes context-dependent: based on the use case, actors and actor roles, and the level of coordination required by the use case, interoperability requirements will be different. There are, however, some common factors for

autonomous mining interoperability. Safety, availability, and production efficiency are goals of the mine owner, whereas OEMs may want to focus on well-defined interfaces to other systems to ensure that the behavior of the systems is predictable.

ISO 15288 includes verification and validation as two distinct, but complementary, processes:

- Verification answers the question: “Are we building the system right?” It focuses on demonstrating that components conform to their specifications. Verification activities typically occur during design, implementation, and integration. Systems are tested to ensure compliance with interface definitions and communication protocols.
- Validation answers the question: “Are we building the right system?” It focuses on demonstrating that the full system fulfils its intended purpose and must be tested under realistic conditions that include the entire system of systems and controls whether systems from different manufacturers can coordinate actions in the mine.

As the mining system of systems evolves to include new or updated components and new missions or tasks within the mine, validation of the SoS may need to be performed again. It will be important to capture the specification of what operations have been validated, using documentation similar to the ODD (operational design domain) used for autonomous mobile machines. The SoS ODD must include details of the SoS and of the mission space for which it is designed. When a new mission is added or a machine is updated, it must then be checked if the SoS ODD also changes: if so, a new validation is required.

Methods for verification and validation

The four strategic paths to interoperability presented earlier in this report (see 5.2.) place different demands on verification and validation activities.

At the component level, interoperability verification is concerned with confirming that systems can connect and exchange information in accordance with established interface specifications. Common practices include interface compliance assessments, protocol conformance checks, and plug tests using equipment from various manufacturers. Plug tests are prevalent across multiple industries; for instance, organizations such as ETSI organize interoperability events where manufacturers test their devices in controlled environments to ensure adherence to interface standards.

Consumer electronics further illustrate this point. Interfaces like USB and HDMI achieve interoperability through rigorous standardization and certification processes, whereby devices are evaluated against standardized criteria to guarantee seamless plug-and-play functionality.

The constituent systems within the mining System of Systems (SoS) are required to undergo similar verification procedures. However, it is insufficient to merely demonstrate message exchange capability; proper interpretation of communicated information and effective task execution by the constellation must also be verified. A constellation refers to a collection of constituent systems collaborating temporarily to accomplish a specific objective, such as transporting material from a loading area to a crusher. The spectrum of tasks expected from the mining SoS should be clearly defined in the SoS Operational Design Domain (ODD), with comprehensive validation conducted to ensure compliance.

Consequently, a mining SoS may exhibit full interoperability for certain missions while lacking it for others, underscoring the necessity of incorporating mission-specific requirements into validation activities.

Fundamental interoperability validation involves ensuring that mobile machines from different manufacturers can exchange and correctly interpret data regarding object identity, position, speed, and heading. Safety considerations necessitate universally comprehensible signals for emergency stop and

halt. Validation for these functions is relatively straightforward, requiring direct connectivity between machines and the transmission of test messages.

Beyond basic interoperability lies the requirement for general awareness regarding the states and intentions of other entities. Machines or vehicles must be able to communicate not only current position and velocity but also intended destination and planned trajectories. This mandates that operational ontologies encompass terms for planned movements, enabling vehicles to convey information such as, “I am proceeding to this location and will traverse these points en route.”

Validation methods here include both simulated environments and practical testing with operational systems from diverse manufacturers tackling real-world scenarios. While validating message exchange for such communications remains uncomplicated, evaluating whether control algorithms can accurately interpret and utilize the information presents greater challenges.

This highlights the importance of semantic interoperability: the capacity to both exchange and correctly comprehend data. Testing must encompass not only routine operations and simulations but also scenarios involving disruptions or unexpected behaviors from system entities.

The concurrent operation of machinery from multiple vendors within the same AOZ requires shared rules for prioritization, including yielding protocols. These guidelines must be integrated into ontologies, and updates regarding rule changes must be readily understood by all participants.

Advancing further in interoperability maturity is the ability to communicate operational intent rather than just trajectories, facilitating collaborative planning and coordination among mobile machines for use case resolution, an essential component for achieving autonomous constellations within the mining SoS.

Finally, the four strategic approaches to interoperability outlined earlier in this report impose distinct requirements on verification and validation activities.

6. Conclusions and future work

Interoperability is a cornerstone for advancing autonomous mining operations, reaching industry visions such as the Zero Entry Mining (Global Mining Guidelines Group, 2025), ensuring seamless collaboration between machines and systems from diverse manufacturers. Currently, the mining sector faces significant fragmentation, with proprietary solutions limiting integration and operational flexibility. Although standards such as ISO 23725 provide a foundation for interoperability, they do not fully address the complexities of real-world deployments and evolving requirements.

The work presented in this report lays a foundation for understanding and advancing interoperability within autonomous mining systems. However, several paths remain open for further exploration and development, both from a technical and organizational perspective. In particular, it is vital to highlight the development of four distinct strategic paths, each representing a different approach to achieving interoperability. Each of the strategic paths have their own technical maturity, challenges and they address different business values. While these paths may address the core functional requirements, they also exhibit varying characteristics in terms of non-functional aspects, often referred to as 'ilities', such as scalability, flexibility, reliability, maintainability, and security. Thorough analysis of these illities is required to ensure that solutions addressing each path are truly scalable and adaptable to future needs, rather than merely solving the immediate functional problem. To further evolve towards a flexible and interoperable mining operation there are several aspects of future work that need to be addressed.

Firstly, activities that aim for more extensive validation of interoperability across additional real-world operational scenarios is required. Future work should involve larger-scale pilot deployments involving a broader range of machines and manufacturers, particularly in environments with increased complexity and more varied disturbances. Furthermore, each solution and its system architecture must be assessed not only for its technical efficacy, but also in terms of its ability to maintain performance under changing operational conditions and its alignment with long-term scalability objectives.

In addition, a comprehensive approach is needed for validating interoperability throughout the entire life cycle of the involved systems. This includes establishing methods and criteria for continuous verification as systems evolve, are upgraded, or integrated with new components. Validation should not be limited to initial deployment or isolated test cases, but must be embedded as an ongoing process, spanning design, implementation, operation, maintenance, and eventual decommissioning. Such an approach will help ensure that interoperability is maintained despite changes in technology, operational requirements, or organizational structures. Developing robust frameworks, automated testing tools, and lifecycle management practices specifically targeting interoperability will be crucial for sustaining seamless collaboration between diverse systems over time.

Secondly, the development and refinement of shared ontologies and rule sets for machine interaction are areas that demand ongoing attention. As new use cases and operational contexts emerge, it will be essential to adapt and expand these ontologies, ensuring that all relevant actors can accurately interpret and respond to messages concerning prioritization and changes in operational rules. Each path may require a tailored ontology or rule set, and their non-functional properties, such as extensibility and interoperability with future systems, must be carefully evaluated to avoid technical debt and facilitate future integration.

In addition, further research is warranted into the trade-offs between increased interoperability and system complexity. While greater interoperability can drive operational efficiency and flexibility, it may also introduce new challenges such as heightened system development costs and the need for more sophisticated coordination mechanisms. Future work should investigate methods for balancing these factors, possibly through advanced simulation, modelling of causal relationships, and the application of decision-support tools such as Pugh matrices or causal loop diagrams. The four solution paths will likely

present different trade-offs between these illities, and a systematic approach to comparing their strengths and weaknesses is essential to inform scalable and future-proof choices.

Another key area for future research is the assessment of business implications arising from different interoperability strategies. This includes analyzing the impact on vendor lock-in, the cost-benefit balance for mine operators, and the broader ecosystem effects as new actors join or exit the system-of-systems. Understanding these business consequences will be vital for guiding both technical and strategic decision-making. Each path may influence these non-functional aspects differently, and a comprehensive analysis must be undertaken to ensure the selected solutions are sustainable and advantageous in the wider business context.

In summary, future work should focus on expanding real-world validation, refining shared models and ontologies, investigating the balance between interoperability and complexity including system diagnostics, evaluating business impacts, and improving the coherence and clarity of methodological communication. Additionally, it is essential to rigorously analyze the four strategic paths and their associated non-functional properties to ensure the chosen strategies are scalable, resilient, and fit for future requirements. Addressing these areas will be key to realizing the full potential of autonomous and interoperable mining systems, not only short term but also long term.

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