Digitalisation in mining operations

Challenges, best practices, and lessons learned from the DINAMINE project

DINAMINE

Co-funded by
the European Union

How to cite this report: DINAMINE Consortium (2026). Digitalisation in mining operations: Challenges, best practices and lessons learned from the DINAMINE project. Zenodo. https://doi.org/10.5281/zenodo.20816898

DINAMINE

The DINAMINE project is supported by the Horizon Europe research and innovation programme (Grant Agreement No. 101091541). Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Health and Digital Executive Agency (HaDEA). Neither the European Union nor the granting authority can be held responsible for them.

PARTNERS

NGI

KEMIJSKI INŠTITUT

AMV EST. 1860

PNO INNOVATION

WORLD SENSING

Skaland Graphite

SINTEF

MCS® PORTUGAL

SPECTRAL INDUSTRIES

Contents

Introduction – Purpose and scope **4**

Objective 4
Target audience 5
Overview of the DINAMINE project 6

1. Identified challenges with digitalisation in the mining sector **7**

1.1 Summary of identified challenges 7
1.2 Conclusion 9

2. Regulations, guidance, and standards in the mining sector – with emphasis on environment, energy and operations **10**

2.1. The regulatory landscape 10
2.2. Operations, environment and energy regulations aspects 12
2.3. The standards landscape in the mining sector 15
2.4. CEN and ISO in the EU mining sector 18
2.5. Digitalisation trends in the mining sector 18
2.6 Relevant policies and regulation linked to the call 22

3. Approaches and implementation in DINAMINE – regulatory landscape **28**

3.1. Environment, energy, and operations standards in the mining sector 28
3.2. Specific standards relevant to the DINAMINE technologies 29
3.3. Alignment of DINAMINE with regulations, standards and frameworks 31

4. Approaches and implementation in DINAMINE – technology solutions **35**

4.1. DINAMINE – the technologies 35
4.2. DINAMINE – addressing identified challenges/barriers 38
4.3 Challenge/Barrier-to-solution mapping 39
4.4. DINAMINE – the modules 43

5. Related HORIZON projects **54**

5.1. Comparative Analysis 55

ANNEX **57**

The key ISO Standards relevant within the Environmental aspects 57
The key ISO Standards relevant within the Operations aspects 58
The key ISO Standards relevant within the Energy aspects 61

Introduction – Purpose and scope

Objective

One of the outcomes of the DINAMINE project is to share knowledge that will foster and accelerate the transition toward a digitalised mining future in small- and medium- sized mining operations. The project developed new technologies and digital solutions that small and medium scale operators in the mining sector can utilize to enable decision-making based on real-time data, advanced analytics, and prognoses. The digital implementations developed during DINAMINE aim to address real-time monitoring, and automation challenges in the mining industry, while realizing environmental, safety and economic benefits of a holistic digitalisation approach.

Developing and demonstrating these technologies provided tangible examples of the opportunities and challenges faced in adoption of new digital tools for planning, monitoring and managing small- and medium-sized mining operations. Therefore, this document may provide value to various stakeholders and similar project initiatives in the future.

While the DINAMINE project was not focused on the standardization of digital tools or any other technology in the mining sector, many of the technological solutions followed accepted standards, described in this document to ensure replicability. Thus, linking the various technologies with the most relevant standards provides an indication of how their implementation can boost this digital transition.

The sections of this report are divided as follows:

1. A summary of the identified challenges that small and medium scale mining operations face, focusing on the barriers and opportunities associated with the adoption of digital solutions. These findings were extracted from market research, and they highlight a combination of financial, technological, organisational, regulatory, and cultural constraints that continue to shape the pace and direction of innovation in the mining sector.
2. An introduction to the regulatory landscape, and the corresponding standards and frameworks, in the mining sector within Europe, with emphasis on environment, energy and operations activities.

3. An overview of the corresponding links between selected standards and the developed technologies in DINAMINE. This approach supports future integration of step-by-step digitalised processes using open interfaces and structured open formats with the scope of complete adoption within several years.
4. A summary of the technology modules that have been developed during the DINAMINE project, together with the lessons learned and the practical solutions that were implemented. These learning points may inform future initiatives.
5. Finally, an outline of initiatives carried out as part of other related HORIZON framework projects and their connection to the regulatory and standards landscape, is provided.

Target audience

There are various stakeholders within the mining sector that are the target audience for this report.

- *Small and medium scale mining operations in Europe:* The main target audience includes: (1) Mines (with focus on relatively small- and medium-scale operations) which have limited investment capacity for digitalisation and upgrading of machinery; and (2) SMEs developing or delivering technologies to assist in mining operations.

  Small and medium sized mining companies can face various challenges when dealing with adopting new digital tools but implementing these solutions can be translated from economic burden into a return on investment. This report describes what first challenges may be encountered, how the DINAMINE project approached these challenges, and recommendations for implementing solutions.

- *Policymakers and organizations that develop standards:* While this report does not provide explicit recommendations toward new regulations or standards, the report outlines the challenges and possible solutions to specific digital challenges within the mining industry, while also identifying an appropriate regulatory landscape for the DINAMINE technologies.

- *Future mining innovation projects:* This document can be used as a reference for future initiatives towards digitalisation of the different technologies, methods, or processes in the mining sector.

Overview of the DINAMINE project

The project aims to transform and modernise the raw materials value chain for small- and medium-sized mining operations by demonstrating technological solutions for more selective, efficient, and sustainable mining practices. The project developed an integrated mine management approach using data analytics tools for real-time monitoring of the performance, risks, mine productivity and recovery rates, and a new drilling machine. Data gathered are analysed in a modular software system that enables mine operators to more accurately plan and manage mine production, predict ore grades and recovery rates, and optimise processing and maintenance requirements. The project has also quantified environmental impacts, identified low emission transportation alternatives, and investigated reuse of mining waste.

Successful implementation of the DINAMINE approach can enable mine operators to take advantage of resources with lower grade ores by making the mining more economically feasible, while fostering the attraction of further investments and stimulating a reshaping of the current practices, technologies, and approaches used in mining operations. This is especially important for REE resources, which typically have irregular geometry, low ore grades, and which are economically marginal. This is achieved through improved productivity of mines and more selective mining, paving the road for future precision mining. The approach will also make currently active mines more resilient toward market fluctuation. Additionally, DINAMINE embeds circularity and sustainability aspects of the raw materials supply chain through tailings monitoring and studying the valorisation potential of tailings and mine waste.

The DINAMINE approach was demonstrated at two small to medium scale European mining operations: an underground graphite mine in Senja, northern Norway and an open pit pegmatite mine in Guarda region, Portugal, and in their associated processing plants. The scaling of the technologies to larger and more complex mining activities involving mining and processing of several types and qualities of ores and orebodies may address the needs of more operators both within the European market and beyond.

1

Identified challenges with digitalisation in the mining sector

The mining sector is undergoing a significant transformation driven by increasing pressure to improve productivity, reduce environmental impacts, enhance worker safety, and secure the long-term supply of critical raw materials. Despite the growing availability of digital and automated solutions, the adoption of innovative technologies within the sector remains fragmented and uneven, especially among small and medium-sized mining operators. A combination of economic, technical, organisational, and regulatory barriers continues to slow the pace of digital transformation. As discussed below, the identified challenges with digitalisation in the mining sector consist of many different factors. Moreover, the project team identified a lack of holistic solutions for small and medium scale operators and a general underappreciation of the potential long-term benefits of investment in digitalisation.

1.1 Summary of identified challenges

Conservative nature of the mining industry. One of the most significant challenges is the traditionally conservative nature of the mining industry. Mining operations are highly dependent on established workflows, and operators are often reluctant to introduce technologies that may disrupt production or require major organisational changes. This is particularly evident in brownfield operations, where retrofitting existing infrastructure with new digital systems can create operational downtime, integration difficulties, and uncertainty regarding return on investment. As a result, many companies adopt a cautious "wait-and-see" approach, preferring to observe proven use cases and successful deployments before committing to large-scale investments.

Financial constraints. The sector also faces major financial constraints linked to the high capital and operational intensity of mining activities. The implementation of advanced digital platforms, automation systems, and intelligent equipment frequently requires substantial upfront investment in software, hardware, connectivity infrastructure, and workforce training. For many small operators, these costs represent a major barrier, especially when combined with uncertainty regarding long-term economic benefits and return on investment. The lengthy purchasing cycles commonly observed in mining further complicate technology uptake, as decision-making processes often involve multiple stakeholders and long-term budget planning.

Digital maturity. Another critical challenge relates to the low level of digital maturity across many mining operations. Although digitalisation is progressing, many companies still rely on fragmented legacy systems, isolated data environments, and manual data management processes. The lack of interoperability between existing software solutions, equipment, and operational databases creates significant obstacles for the integration of new technologies. In many cases, mining operations generate large amounts of data that remain compartmentalised across departments, limiting real-time visibility, operational optimisation, and effective decision-making.

Technical complexity. Technical complexity also represents a substantial barrier to adoption. Mining environments are highly heterogeneous, with different geological conditions, operational requirements, and infrastructure constraints depending on the type and location of the mine. This diversity limits the effectiveness of “one-size-fits-all” solutions and requires technologies to be adaptable, modular, and capable of integrating with existing operational ecosystems. Furthermore, mining operations are often located in remote areas where connectivity infrastructure and reliable internet access remain limited, creating additional difficulties for cloud-based systems, remote monitoring, and autonomous operations.

Cybersecurity and data protection. Cybersecurity and data protection concerns are becoming increasingly important as mining operations become more connected and data driven. The growing integration of sensors, IoT devices, autonomous equipment, and cloud-based platforms expands the attack surface of mining operations, exposing companies to cyber threats and operational vulnerabilities. Ensuring secure data management, controlled access to sensitive operational information, and compliance with evolving digital regulations has therefore become a strategic challenge for technology providers and mining operators alike.

Digital transition. The mining workforce is also facing a period of transition. The sector is experiencing an ageing workforce combined with difficulties in attracting younger generations and digitally skilled professionals. This skills gap creates challenges for the implementation and maintenance of advanced technologies, especially in small companies with limited internal IT capabilities. Resistance to automation and digitalisation can also emerge among workers and middle management due to concerns about job displacement, increased complexity, or lack of familiarity with digital systems. Consequently, successful technology adoption increasingly depends on the availability of training, user-friendly interfaces, technical support, and workforce reskilling initiatives.

External pressures. At the same time, mining companies are facing growing environmental, social, and governance pressures. Regulatory frameworks related to emissions reduction, environmental monitoring, waste management, worker safety, and sustainability reporting are becoming stricter across Europe and globally. Mining operators are expected not only to comply with these regulations but also to demonstrate transparent environmental and social performance to regulators, investors, local communities, and the wider public. Securing and maintaining a social license to operate has therefore become a central concern for the industry. Public opposition to mining projects, especially in environmentally sensitive or densely populated areas, further increases the need for technologies that support transparency, sustainability, and safe operations.

Operational safety. Safety remains another major challenge for the sector, particularly in underground mining environments where workers are exposed to potentially hazardous conditions, heavy machinery, rockfalls, dust, noise, and complex geotechnical risks. As ore deposits become more difficult to access and mining activities move deeper underground, the need for remote operations, automation, real-time monitoring, and predictive safety systems becomes increasingly critical.

Innovations. The rapid pace of technological innovation also creates challenges for mining companies attempting to modernise their operations. While automation, artificial intelligence, predictive analytics, IoT systems, and digital twins offer significant opportunities, mining organisations often struggle to align technological development with workforce capabilities, organisational readiness, and operational practices. In many cases, technological progress evolves faster than the sector's ability to adapt its internal structures, skills, and decision-making processes.

Competitive digital landscape. Finally, the competitive landscape of the mining technology market presents additional pressures. Large multinational companies already dominate several segments of the mining software and automation market, offering highly advanced but often expensive and complex solutions. Smaller mining operators frequently lack access to flexible and affordable alternatives adapted to their operational realities. This creates a clear need for modular, scalable, and interoperable technologies capable of supporting progressive digital transformation while remaining accessible to small and mid-sized mining companies.

1.2 Conclusion

Overall, the mining sector faces a combination of structural, economic, technical, social, and regulatory challenges that continue to slow the adoption of digital and automated solutions. Addressing these barriers requires not only technological innovation, but also approaches that prioritise interoperability, user acceptance, workforce integration, scalability, cybersecurity, affordability, and alignment with sustainability and safety objectives. The transition toward a more digital, automated, and sustainable mining industry will therefore depend on the ability of innovative solutions to respond effectively to these interconnected challenges while demonstrating tangible operational, environmental, and economic benefits.

A comparative analysis of the two DINAMINE project pilots shows a strong convergence of findings. Despite differences in company size, geography, and operational focus, interviewees from both pilots identified similar structural challenges affecting the sector. Financial constraints, interoperability and system integration difficulties, shortages of specialised digital skills, and increasing pressures related to social license and environmental compliance emerged consistently across the discussions.

These findings are further corroborated by the results of a market outlook analysis, performed during the project, which identified comparable barriers at the broader market level. The market research highlighted high CAPEX and OPEX intensity, lengthy purchasing cycles, cultural resistance to change, digital immaturity, interoperability limitations, and regulatory complexity as systemic constraints slowing digital transformation across the mining sector in Europe.

The recurrence of these issues across independent company interviews and market research suggests that they are not company-specific obstacles, but rather systemic and structural challenges shaping the broader European mining ecosystem. This triangulation of evidence strengthens the validity of the identified barriers and underscores the need for coordinated sector-wide responses that address financial, technological, organisational, and regulatory dimensions simultaneously.

2

Regulations, guidance, and standards in the mining sector – with emphasis on environment, energy and operations

2.1. The regulatory landscape

Regulatory frameworks in the mine life cycle comprise a sequence of legal, environmental, and social compliance requirements from exploration to post-closure. Key stages include permitting exploration activities, environmental impact assessments (EIA) during development, operational licenses for health and safety, and reclamation bonds for closure, ensuring adherence to local laws and international standards. They are focused on environmental protection, safety, and community impacts.

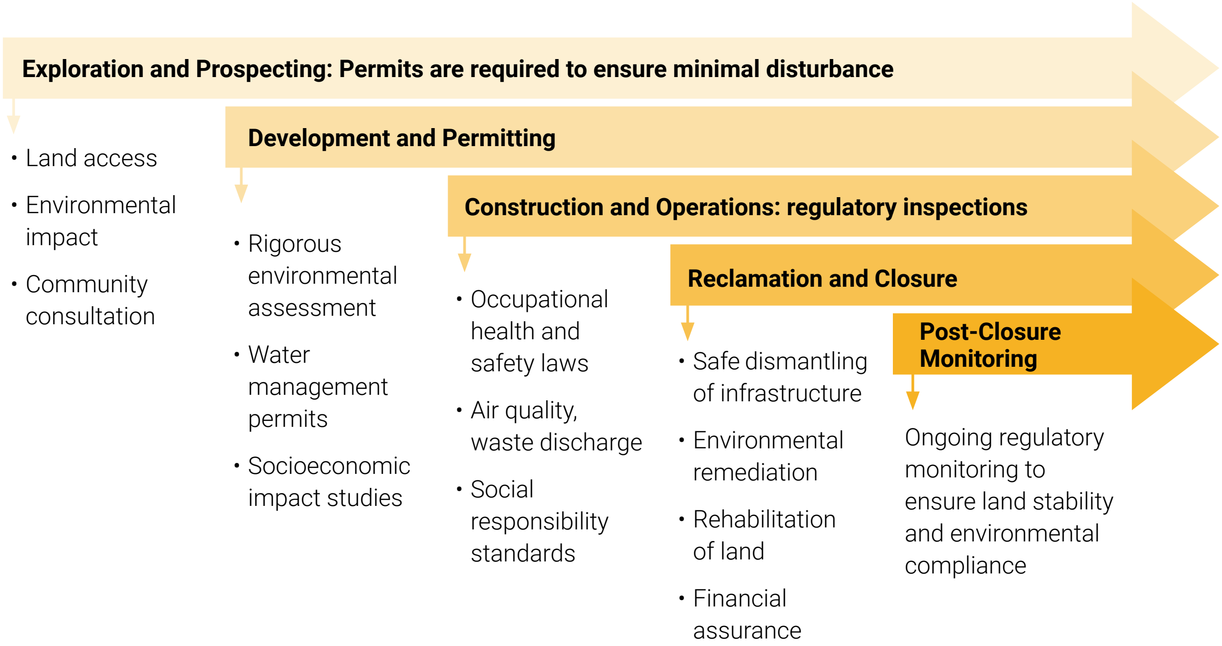
European mining regulations focus on accelerating domestic production of critical raw materials while adhering to strict environmental and social standards. Key legislation includes the 2024 Critical Raw Materials Act (CRMA), aiming for 10% domestic extraction by 2030, alongside the Mining Waste Directive, the regulation on the registration, evaluation, authorisation and restriction of chemicals (REACH), environmental impact assessments (EIA), and Conflict Minerals Regulation.

As an overview, the regulatory landscape during the life cycle of the mine is listed as follows:

Key Regulatory Stages in the Mining Life Cycle

- *Exploration and Prospecting:* Regulations focus on land access, environmental impact of drilling, and community consultation. Permits are required to ensure minimal disturbance.
- *Development and Permitting:* This phase requires rigorous environmental assessment, water management permits, and socioeconomic impact studies. Companies often must submit detailed closure plans before construction.
- *Construction and Operations:* Governed by occupational health and safety laws, air quality, waste discharge, and social responsibility standards. Regulatory authorities conduct inspections to ensure compliance with operating permits.

- *Reclamation and Closure:* Focuses on safe dismantling of infrastructure, environmental remediation, and rehabilitation of land. Financial assurance or bonds are often required to ensure funding for closure activities.
- *Post-Closure Monitoring:* Ongoing regulatory monitoring to ensure land stability and environmental compliance (e.g., water quality) long after mining operations cease.



The Key Regulations Pillars in the mining sector are:

Critical Raw Materials Act (CRMA) (2024) (described in more detail in Section 2.6)

Sets benchmarks to diversify imports and boost domestic capacity (10% extraction, 40% processing, 25% recycling by 2030). It streamlines permitting, limiting the time for authorization processes for strategic mines.

EU Conflict Minerals Regulation (2021)

Obliges EU companies importing tin, tantalum, tungsten, and gold (3TG) to perform due diligence to ensure supply chains do not fuel conflicts or human rights abuses.

Environmental Protection

Environmental protection in the European mining sector is primarily governed by the Mining Waste Directive (2006/21/EC), which regulates waste management, and the Environmental Liability Directive (2004/35/EC), enforcing the "polluter pays" principle. Key regulations include water protection, air quality standards, and mandatory environmental impact assessments (EIA), often requiring financial guarantees for closure and rehabilitation.

Safety and Standards

The Basic Safety Standards Directive (2013/59/EURATOM) addresses radioactive waste, particularly relevant to rare earth element mining.

Sustainability and Transparency

Companies must adhere to reporting guidelines, often following ESG impact assessments, and manage water resources according to the Water Framework Directive.

The License to Operate (LTO) refers to the formal and informal approvals a company needs from governments, investors, communities, and other stakeholders to begin and continue operations. Increasingly, the LTO is not just a regulatory permit, it is a social, environmental, and governance mandate and certification. ESG compliance is often a prerequisite for stakeholder support, financing, and project approval, positioning ESG adherence as central to securing and maintaining a mining company's long-term LTO. In practice, this means mining companies must demonstrate responsible behaviour, environmentally, socially, and ethically, before investors, communities, and even downstream buyers accept their products or their presence.

2.2. Operations, environment and energy regulations aspects

The aforementioned regulations cover health and safety, environmental protection, and operational procedures, often managed through a mine safety management system. Key areas include risk management, hazard identification, emergency planning, air quality, and sustainable practices like water conservation and renewable energy.

Within the DINAMINE project, the digital implementations developed are aligned with the aspects of energy, environment and operations covered by the regulatory pillars mentioned in Section 2.1. Moreover, these three aspects are an interdependent system, and their scope tends to overlap; therefore, it is difficult to treat them as isolated aspects. Nevertheless, by describing their scope and some of the key frameworks, it is possible to describe their relevance to the DINAMINE solutions:

2.2.1. Environmental Regulations

Environmental compliance is a prerequisite for obtaining a LTO and to have access to capital. The companies' commitments include demonstrating responsible environmental practices, such as waste management, biodiversity protection, and carbon footprint reduction. The regulations that are focused on the environmental aspects include:

Mining Waste Directive (2006/21/EC)[1]

The European Mining Waste Directive sets strict standards for managing waste from extractive industries to protect human health and the environment. It requires operators to create waste management plans, obtain permits, and ensure long-term facility stability, with specific, stringent rules for hazardous "Category A" sites. The scope and application cover waste from prospecting, extracting, treating, and storing mineral resources, as well as quarrying. The core requirements of the Directive are:

- Waste Management Plans: Operators must submit plans that prioritize waste prevention, reduction, recycling, and recovery.
- Financial Guarantees: Companies must provide financial assurance before starting operations to ensure that waste sites are properly closed and monitored afterward.

1 https://environment.ec.europa.eu/topics/waste-and-recycling/mining-waste_en

- Safety & Prevention: The directive mandates major-accident prevention policies (similar to Seveso standards) and requires regular inspections of waste facilities.
- Environmental Protection: It mandates measures to prevent water pollution, soil contamination, and air pollution, particularly for tailings ponds and waste rock dumps.
- Category A Facilities: Specific, higher-level safety and structural requirements apply to high-hazard facilities.
- Tailings Management: Strict requirements for the design, management, and closure of tailings ponds, including mandatory financial guarantees to cover environmental liabilities.

Environmental Liability Directive (2004/35/EC)

Holds operators financially liable for preventing and remedying environmental damage.

Environmental Impact Assessment (EIA) Directive[2]

(2011/92/EU as amended by 2014/52/EU) EIA is defined as the analysis and evaluation of possible environmental impacts of proposed decisions or activities likely to cause significant effects on the environment. The assessments will help to arrive at informed decisions, set development conditions and serve as a basis for follow-up and monitoring of the implementation of decisions. The projects require projects to undergo strict environmental impact assessments before authorization. Also, it regulates environmental assessments for mining projects, requiring assessment of environmental impacts (water, air, fauna) and mitigation measures for significant projects.

Water Framework Directive (2000/60/EC)[3]

Governs the protection of water bodies, crucial for mining operations, with revisions planned for 2026 to align with raw material demand. Also, Water Management & Protection Regulations strictly regulate water quality, discharge, and usage, demanding treatment of process water and prohibition of pollution in water bodies. Groundwater Protection: Directive 2006/118/EC specifically focuses on preventing pollution in groundwater systems.

Industrial Emissions Directive (2010/75/EU)

The Industrial Emissions Directive (IED) is a European Union directive which commits European Union member states to control and reduce the impact of industrial emissions on the environment. The directive aims to lower emissions from industrial production through an integrated approach. The revised EU Industrial Emissions Directive (IED 2.0), adopted in April 2024 and in force since August 4, 2024, aims to drastically reduce pollution from large industrial installations and livestock farms, supporting EU climate neutrality by 2050. It forces stricter emission limits, expands coverage to include more mining and battery manufacturing, increases public participation, and allows citizens to claim compensation for health damages from illegal pollution.

Seveso III Directive (2012/18/EU)

Controls major accident hazards involving dangerous substances in mining tailings.

2 https://environment.ec.europa.eu/law-and-governance/environmental-assessments/environmental-impact-assessment-eia_en

3 https://environment.ec.europa.eu/topics/water/water-framework-directive_en

REACH Regulation[4]

Manages risks from dangerous chemicals used in mining processes.

The EU Soil Strategy for 2030[5]

A key component of the European Green Deal, aims to achieve healthy, non-degraded soils by 2050 through restoration and sustainable management. It is centred on harnessing the numerous benefits that healthy soils provide, which are vital for human well-being: sustainable food production, biodiversity and climate resilience. Regarding the mining sector, the strategy focuses on reducing the environmental impact of extraction, reclaiming land, and managing excavated materials sustainably.

The Corporate Sustainability Reporting Directive (CSRD)

The Corporate Sustainability Reporting Directive (CSRD), adopted in December 2022, fundamentally transforms sustainability reporting for the mining sector by making it mandatory, rigorous, and comparable to financial reporting. For mining companies, which often have high environmental and social impacts, the CSRD mandates detailed disclosures on environmental, social, and governance (ESG) factors across their entire value chain.

2.2.2. Operational Regulations and Compliance

Mining operations in Europe are governed by a complex framework of European Union (EU) directives, regulations, and national laws focusing on environmental protection, safety, and sourcing, as described above. As of 2026, the regulatory landscape is shifting to prioritize domestic production of critical raw materials through streamlined permitting while enforcing stricter sustainability standards. Due to increased digitalisation and the rise of widespread generative artificial intelligence (AI) models, the regulations have been adapting their frameworks, to the use of autonomous trucks and drones, with AI becoming a feature of ESG management and reporting. The key regulatory pillars include the aforementioned environmental regulations, as well as the following:

Strategic & Operational Frameworks (EU Level); includes the CRMA and Conflict Minerals Regulation, and in addition:

- RESourceEU Action Plan (2026): A 2026 strategy accelerating the CRMA with €3 billion in funding for strategic mining and processing projects.
- Industrial Accelerator Act Proposal (2026): A proposed 2026 initiative aimed at speeding up industrial capacity and decarbonization in strategic sectors

Occupational Health and Safety

- Mineral-Extracting Industries Directive (92/91/EEC): Specific minimum requirements for safety and health protection, particularly for drilling and underground extraction.
- Occupational Safety Directives (89/391/EEC & 92/91/EEC): Establish minimum requirements for safety and health protection of workers, including the implementation of dust suppression systems (e.g., water sprays) and managing underground engine exhaust emissions. Directive 89/391/EEC (the "Framework Directive") establishes general principles for EU occupational health and safety (OSH), mandating risk assessments, prevention, and training. Directive 92/91/EEC is an individual "daughter" directive focusing specifically on safety in mineral-extracting industries through drilling.

4 https://environment.ec.europa.eu/topics/chemicals/reach-regulation_en

5 https://environment.ec.europa.eu/topics/soil-health/soil-strategy-2030_en

Upcoming Changes and 2026 Trends

- Industrial Accelerator Act Proposal (2026): A proposed act to boost the manufacturing sector, streamline permit granting, and increase economic security.
- 2040 Climate Targets: New regulations in 2026 (EU 2026/667) set a 90% net reduction in greenhouse gas emissions by 2040, impacting mining carbon emissions.
- Forced Labour Regulation (EUFLR): Expected to ban products made with forced labor by the end of 2027.
- Water Law Revisions (2026): Revisions are underway to balance industrial needs for raw materials with environmental protection, often causing tension with stricter environmental protections.
- Waste and Circularity: New 2026 restrictions are being implemented on the export of critical waste, including scrap from permanent magnets and aluminium, to boost local recycling.
- Digitalization and Automation: Regulations are evolving to manage risks related to AI and automated mining technology.
- Carbon Border Adjustment Mechanism (CBAM): By 2026, the final regime applies to carbon-intensive imports (e.g., steel, aluminum).

2.2.3. Energy Transition and Regulatory Trends

Energy regulations for the mining sector in Europe are heavily driven by the EU Green Deal, aiming for climate neutrality by 2050, with a focus on decarbonization, energy efficiency, and securing critical raw materials (CRMA). The key regulations focused on the energy transition, which includes CRMA, are:

Renewable Energy Directive (RED III - 2023/2413)

Increases the binding 2030 renewable energy target to at least 42.5% (aiming for 45%). It requires Member States to designate "renewables acceleration areas" with streamlined permits by February 2026.

Energy Efficiency Directive (EED - 2023/1791)

Mandates an 11.7% reduction in final energy consumption by 2030, with mandatory energy audits every 4 years for large users or implementing an energy management system.

EU Methane Regulation (2024)

Introduces stringent monitoring, reporting, and verification (MRV) of methane emissions, with bans on venting and flaring for both active and closed coal mines.

2.3. The standards landscape in the mining sector

The relationship between the European regulatory framework for mining and the standards developed to support them, has a symbiotic "law-to-standard" relationship, where legislation sets the mandatory legal goals, while the technical standards (voluntary or harmonized) define the specific, measurable methods to achieve them. Standards[6] serve as the operational tool based on the EU policy objectives and convert the requirements into practical mining operations[7].

6 Standards are voluntary guidelines that set out how products, services, and business processes should work. They provide the technical specifications that help make things safe, reliable and easy to use. Standards cover almost everything from safety helmets and phone chargers to accessibility requirements in public transport.

7 https://europa.eu/youreurope/business/product-requirements/standards/standards-in-europe/index_en.htm

While the use of standards is voluntary, adopting them can bring important benefits such as improved safety and quality, increased consumer confidence, and access to new market opportunities. In some cases, standards are referenced in the legislation as a preferred way or even as a mandatory requirement to comply with specific laws (i.e. safety legislation or interoperability requirements). While not legally mandated, standards are recognized as the highest benchmarks for compliance, covering worker rights, community engagement, and environmental impact. The implementation of standards helps companies reduce environmental impacts, improve transparency, manage risks, and align with global frameworks like the UN Sustainable Development Goals (SDG) and the Paris Agreement. As mining expands to meet rising demand for critical minerals, harmonized and robust standards are increasingly important for improving social outcomes, enabling responsible investment, and supporting long-term sector sustainability.

Standards Development Organizations (SDOs) are the entities, ranging from non-profits to government agencies, that create, maintain, and publish voluntary technical standards across global industries. The major international SDO includes

- ISO (International Organization for Standardization), which develops voluntary international standards for nearly all industries.
- IEC (International Electrotechnical Commission): Focuses on standards for electrical and electronic technologies.
- ITU (International Telecommunication Union): Focuses on telecommunication standards.

Within the mining sector, SDOs and industry bodies in Europe focus on harmonizing safety, environmental, and operational standards, often in conjunction with European Commission policies like the CRMA. The key organizations, initiatives, associations, and standards bodies are listed in the next section.

2.3.1. Key European Mining Standards Bodies & Associations

- *Euromines*[8] is the primary recognized voice of the European metals and minerals mining industry. It represents 19 national mining federations and 16 major mining companies, advocating for responsible industry practices in EU policymaking, including health and safety and environmental standards.
- *VDMA Mining & Minerals* represents about 160 European (primarily German) mining technology suppliers, focusing on technical standards for mining machinery and equipment.
- *CEN/CENELEC* is the European Committee for Standardization and European Committee for Electrotechnical Standardization, which develop harmonized standards for machinery and worker safety in the European sector.
- *European Partnership for Responsible Minerals (EPRM)* is a multi-stakeholder partnership aiming to increase the number of mines adopting responsible practices in conflict-affected and high-risk areas (CAHRAs).
- *ISO Standards (ISO 9001/14001):* While international, these are heavily used to set quality and environmental benchmarks for Europe in all industries.

2.3.2. Major Standards Initiatives & Frameworks Used in Europe

The different initiatives developed in Europe, and world-wide, act as a bridge, unifying major voluntary sus-

8 https://euromines.org/

tainability standards into a single, comprehensive framework designed to align the mining activities with the strict European regulations.

- IRMA (Initiative for Responsible Mining Assurance): An increasingly influential, comprehensive standard for industrial-scale mining, often referred to in European discussions on responsible sourcing. It is recognized as a high-bar, best-practice standard for responsible mining, with the European Parliament encouraging its use as a benchmark for compliance.
- CMSI (Consolidated Mining Standard Initiative): A new industry-led initiative designed to consolidate existing standards (ICMM, Copper Mark, MAC, WGC) into a single, comprehensive framework to simplify compliance and increase adoption, aiming to meet EU criteria.
- ICMM (International Council on Mining and Metals): Its 10 Principles are a global standard adopted by many large mining companies operating in Europe, these include ethical governance, integration of sustainable development, human rights protection, risk management, health and safety, environmental performance, and biodiversity conservation. The ICMM aligns with global frameworks such as the UN SDGs, Paris Agreement, and OECD guidelines, and offers credible assurance processes at both corporate and site levels, and it is a key partner in the CMSI. Additionally, ICMM's involvement in the Global Industry Standard on Tailings Management (GISTM) enhances public safety and environmental security—both critical to maintaining LTO.
- GRI (Global Reporting Initiative) 14: A comprehensive, multi-stakeholder reporting framework that provides transparent, standardized metrics for reporting impacts, which helps companies comply with EU transparency regulations (effective Jan 1, 2026).
- EITI (Extractive Industries Transparency Initiative): Often supported by European standards to ensure transparency in mining governance and revenue.
- Global Cross Industry Standards are frameworks, protocols, and best practices adopted across various sectors to ensure consistency, interoperability, safety, and efficiency on a global scale. These standards bridge digital and physical worlds, facilitating smoother international trade and innovation.
- The European Raw Materials Alliance (ERMA)[9] contributes to ensuring a reliable, secure and sustainable access to raw materials. ERMA's vision is to secure access to critical and strategic raw materials, advanced materials, and processing know-how for EU Industrial Ecosystems. The alliance involves all relevant stakeholders, including industrial actors along the value chain, Member States and regions, trade unions, civil society, research and technology organisations, investors and NGOs.

9 https://erma.eu/

2.4. CEN and ISO in the EU mining sector

CEN (European Committee for Standardization[10]) and ISO (International Organization for Standardization) have a close technical partnership established by the Vienna Agreement (1991) to ensure technical alignment, reduce duplication, and prioritize the adoption of international standards as European standards. While CEN operates at the European level, this relationship allows for information exchange and joint development of standards. Both organizations can work together on the development of new standards to ensure they are accepted at both the European and international levels. As well, the agreement ensures that if an international standard (ISO) meets European requirements, it is adopted as a European standard (EN) to foster market access.

ISO standards are frequently used in conjunction with the EIA Directive to provide a regulated, structured framework for environmental assessment throughout the entire lifetime of mining projects. While the EIA Directive mandates the initial assessment and licensing, ISOs standards manage environmental impacts during the operation, closure, and post-closure phases.

Key ISO Standards applicable to the life cycle of a mining operation include:

- ISO 14001 (Environmental Management Systems): This is the most widely adopted standard in mining to identify and manage environmental impacts, such as water pollution, waste production, and greenhouse gas emissions.
- ISO 45001 (Occupational Health and Safety Management): This standard provides a framework for reducing workplace hazards and fatalities in mining environments.
- ISO 50001 (Energy Management Systems): This standard helps mining companies reduce operating costs and improve energy efficiency, which is vital given the energy-intensive nature of extraction.
- ISO 31000 (Risk Management): Provides guidelines for systematically identifying, assessing, and mitigating risks, including operational, safety, and environmental risks.
- ISO 14064 (Greenhouse Gas Emissions): Sets requirements for quantifying and reporting GHG emissions, assisting with climate action strategies.
- ISO 26000 (Social Responsibility): Offers guidance on ethical business practices, including community engagement and human rights.

2.5. Digitalisation trends in the mining sector

2.5.1. Layered, open-protocol architectures

The dominant trend among European mine operations that have moved beyond first-generation SCADA is the adoption of a layered architecture inspired by ISA-95 / RAMI 4.0[11] and the Unified Namespace (UNS) pattern, rather than a single-vendor mine management suite. The pattern, in increasing order of abstraction, is:

- Field instrumentation layer with open or de-facto-open protocols: OPC UA, MQTT/Sparkplug B, Modbus TCP, LoRaWAN for low-power wide-area sensing, NB-IoT/LTE-M for cellular telemetry, leaky feeder and increasingly private 5G/LTE or Wi-Fi 6 for high-bandwidth underground/pit applications.
- Edge computing on industrial gateways (typically Linux-based, vendor-agnostic) handling local pre-processing, store-and-forward, and safety-critical loops that cannot tolerate cloud latency.

10 https://www.cencenelec.eu/about-cen/cen-and-iso-cooperation/

11 ISA-95 is an international standard for integrating enterprise business systems (like ERP) with factory floor control systems (like MES and SCADA). RAMI 4.0 is an expanded architectural framework designed for Industry 4.0, which builds upon ISA-95.

- Integration / data fabric layer: a broker (MQTT) plus a time-series historian - open-source options (TimescaleDB, InfluxDB) and lighter commercial historians are increasingly displacing AVEVA PI for new deployments where the licensing footprint of PI is disproportionate.
- Application layer: best-of-breed modules for fleet management, EMS, EH&S, CMMS, geotechnical monitoring, etc., communicating through the data fabric rather than via point-to-point integrations.

The strategic value of this architecture is that the integration substrate is owned by the operator, not the vendor. Each application module becomes individually replaceable. The trade-off is that the operator assumes the integration burden internally or via a system integrator, including responsibility for the data model (asset hierarchy, tagging conventions, master data). Without governance, a "modular" estate degenerates into ad-hoc point integrations that are no better than a closed ecosystem and arguably worse for cybersecurity.

The OEM ecosystem comparison is useful as a benchmark, e.g. Sandvik AutoMine / OptiMine, Epiroc Mobilaris / Certiq, Komatsu Modular Dispatch etc., offer faster time-to-value and a single accountable supplier, at the cost of (i) capital lock-in to that OEM's mobile fleet, (ii) opaque data ownership terms in some contracts, and (iii) limited extensibility to non-OEM equipment, which is acutely problematic for mine companies running mixed fleets.

2.5.2. Operational digitalisation

For small and medium sized operators, the highest-leverage operational digitalisation currently sits in four areas, in approximate order of payback maturity:

1. Short-interval control and dispatch

Mid-tier and modular fleet management / dispatch products (e.g. Maptek, Micromine Pitram, MineRP, Datamine, Deswik IPCC, RCT ControlMaster for partial automation, and several open-source-derived stacks emerging from European H2020/Horizon Europe projects such as NEXGEN SIMS and illuMINEation[12]) offer functionality that 5–10 years ago required a tier-1 OEM commitment. Evidence on productivity uplift is mixed and site-specific; published gains of 10–20% on tonnage moved per shift are credible for greenfield deployments but should not be taken as universal.

2. Drill-and-blast digitalisation

Measurement-while-drilling (MWD) data capture, drill navigation, electronic detonator integration, and blast vibration/airblast monitoring are now feasible without OEM lock-in. The supporting ecosystem — Strayos, BlastIQ-equivalent third-party stacks, Hexagon MineProtect for some functions — is maturing.

3. Condition-based and predictive maintenance

Small and medium sized operators typically gain more from disciplined condition monitoring (vibration, lubricant analysis, IR thermography) integrated into a mid-weight CMMS (Fiix, Limble, IBM Maximo Application Suite at the upper end) than from heavy AI-based predictive solutions, where the data volumes from a mid-size fleet are usually insufficient to train robust models without external data pooling.

4. Geotechnical and pit/wall monitoring

Slope stability radar, robotic total stations, MEMS tilt/inclination sensor networks, piezometers, MPBX

12 A multi-level IIOT platform for boosting mines digitalization, DOI 10.1016/j.future.2024.107501

extensometers, and InSAR (including free Copernicus Sentinel-1 baseline) are converging into modular geotechnical platforms. This is one of the areas where European specialist vendors compete strongly with OEM offerings.

2.5.3. Energy digitalisation

In a typical metalliferous mine, comminution accounts for 30-50% of total electrical energy demand, ventilation (in underground operations) for 25-40%, compressed air for 5-15%, and materials haulage for the balance. Digitalisation interventions track this distribution:

- ISO 50001-aligned Energy Management Systems at site level, fed by sub-metering at process unit level, are the foundation. Modular EMS options (Schneider EcoStruxure Power Monitoring Expert, Siemens SIMATIC Energy Manager, and lighter-weight cloud platforms such as Dexma/Spacewell or DEXMA, EnergyElephant) compete credibly against OEM-bundled offerings.
- Comminution optimisation through advanced process control on SAG/ball mills - particle-size monitoring, mill load and bearing pressure analytics, expert-system control layers (Process IQ, KnowledgeScape, Stone Three) - typically yields 3–8% specific energy reduction (kWh/t milled) where baseline control is mature, more where baseline is poor. Evidence is robust in published literature but site-specific.
- Ventilation-on-Demand (VoD) for underground operations is one of the highest-payback digitalisation interventions documented, with case-study savings frequently in the 30–50% range on ventilation electrical load. Modular vendors -Howden Ventsim Live, Maestro Digital Mine, Bestech NRG1-ECO, ABB Ventilation Optimizer- operate independently of mobile fleet OEMs. The prerequisite is reliable underground tracking (people and equipment) and adequate communications infrastructure.
- Compressed air leak management and demand-side optimisation is a low-capital quick win, typically tackled with portable ultrasonic survey tools plus permanent flow/pressure metering tied to the EMS.
- Renewable integration and microgrid optimisation is emerging rapidly for European SMEs, particularly in Iberia, Scandinavia, and parts of the Balkans. Energy management here overlaps with grid-services optimisation (hybrid PPA strategies, balancing market participation) and is increasingly supported by digital-twin tools modelling the production–energy nexus.

A caveat is that claims of energy savings from individual digital interventions often double-count when stacked. A defensible business case anchors savings to measured kWh against an ISO 50006 / IPMVP-compliant baseline, not to vendor-stated typical values.

2.5.4. Environmental digitalisation

The regulatory pressure is a combination of:

- CSRD / ESRS (mandatory sustainability reporting for most EU mines, with site-level KPIs)
- the EU Battery Regulation and the Conflict Minerals Regulation, both demanding traceability
- the Industrial Emissions Directive (IED) BAT conclusions for non-ferrous metals
- the Mining Waste Directive 2006/21/EC
- adoption of the Global Industry Standard on Tailings Management (GISTM), increasingly demanded by financiers and insurers.

This implies that environmental instrumentation is shifting from "optimisation" to "compliance with auditable digital evidence." This shift favours modular, well-instrumented architectures over OEM ecosystems that may not export environmental data freely.

Common building blocks include:

- Tailings storage facility (TSF) instrumentation: vibrating-wire piezometers, inclinometers, settlement monitoring, perimeter prisms with robotic total stations, increasingly InSAR monitoring.
- Water management: multiparameter sondes (pH, conductivity, turbidity, dissolved O_2, ORP) at influent/effluent points, integrated water-balance modelling (GoldSim, MIKE, or open tools).
- Air quality and dust: TSP/PM10/PM2.5 monitors with real-time telemetry; NOx and SOx near processing.
- Noise and ground vibration: perimeter monitoring with thresholds tied to permit conditions.
- Greenhouse gas (GHG) inventory and Scope 1/2/3 reporting: increasingly automated by pulling fuel, electricity, and process data from the operational data fabric — a strong argument for modular architectures, since the GHG accounting tool needs trusted access to all of those streams.
- Earth-observation augmentation: the CRM Resilience Communication[13] explicitly identifies Copernicus as a tool for monitoring environmental performance during operation and post-closure (Action 7). For small and medium sized operators, free Sentinel data plus low-cost commercial cueing services can replace or complement substantial ground instrumentation.

13 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52020DC0474

2.5.5. Cross-cutting trends

Connectivity is the most underestimated bottleneck. A modular architecture is only as good as its data plumbing. Choices among LoRaWAN (low-power wide-area, excellent for environmental and slow-process telemetry), NB-IoT/LTE-M (where carrier coverage exists), private LTE/5G (capital-intensive but increasingly viable for medium operations with mixed pit/underground needs), and traditional leaky feeder (still dominant underground for voice/safety) need to be made deliberately, with use-case requirements mapped to RF bands, latency, and reliability targets.

Cybersecurity / NIS2. The NIS2 Directive (Directive (EU) 2022/2555[14]), transposition deadline 17 October 2024, classifies many medium mines as "important" or potentially "essential" entities depending on size and minerals criticality. This imposes incident reporting, risk management, and supply-chain security obligations that materially raise the bar for any digitisation project. Modular architectures must be designed with IEC 62443 zone/conduit segmentation from the outset.

Skills and operating model. The Digital Compass and CRM Communication both flag the skills gap as the binding constraint, particularly in the small and medium sized operator segment. A modular strategy presupposes either internal data engineering capacity or a long-term system integrator partnership; this should be costed into the business case alongside the licensing differential vs. OEM ecosystems.

Funding instruments. Horizon Europe (Research & Innovation projects on CRM extraction/processing - Action 8 of the CRM Resilience Communication), Just Transition Fund (for coal-region transitions), InvestEU sustainable infrastructure window, and national instruments are actively funding digitalisation in this segment. For small and medium sized operators, this can shift the build-vs-buy and modular-vs-OEM calculus materially.

2.6 Relevant policies and regulation linked to the call[15]

Research and innovation will continue to be fundamental to the modernisation of traditional industrial models while developing novel technologies, business models and processes. This should in turn enhance the flexibility of the EU's industrial base and increase its resilience by reducing Europe's dependence on third countries for critical raw materials and technologies.

The most relevant policies of the European Commission, that are related to the call of the HORIZON funding scheme that provided grant funding to the DINAMINE action, are described in the following sub-sections.

2.6.1. Regulation (EU) 2024/1252 (Critical Raw Materials Act)

Regulation (EU) 2024/1252 (Critical Raw Materials Act) provides a comprehensive policy framework that directly underpins the development of sustainable mining projects within the European Union. By establishing legally binding benchmarks for domestic extraction, processing, and recycling, limiting on external dependencies, the Regulation creates both regulatory certainty and strategic incentives for investment across the entire raw materials value chain[16].

Within this framework, sustainable mining projects are positioned as a critical component of achieving the EU's target of sourcing at least 10% of its annual consumption of strategic raw materials domestically.

14 https://eur-lex.europa.eu/eli/dir/2022/2555/oj/eng

15 https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/topic-details/horizon-cl4-2022-resilience-01-06

16 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:L_202401252

These projects are further supported through the designation of Strategic Projects, which benefit from streamlined permitting procedures, improved access to financing, and coordinated administrative oversight, thereby reducing typical barriers associated with mineral development in Europe.

Importantly, the Regulation does not promote mining expansion in isolation but embeds it within a broader system of environmental safeguards, circular economy principles, and resource efficiency requirements. Sustainable mining projects are therefore expected to operate in alignment with stringent EU environmental legislation, while also contributing to downstream recycling, waste recovery, and reduced lifecycle impacts.

Moreover, the Act integrates mining into a holistic and interdependent supply chain model, where extraction, processing, recycling, and substitution are treated as complementary rather than separate activities. This systems-oriented approach reinforces the role of sustainable mining as both a primary supply source and an enabler of circular material flows, particularly through the recovery of critical raw materials from extractive waste and secondary sources.

Projects aligned with the Critical Raw Materials Act should demonstrate a contribution to a secure, diversified, and sustainable supply of critical raw materials in Europe, while adhering to strict environmental, social, and governance standards. Specifically:

1. Contribution to EU Supply Security and Strategic Targets
   - Target resources classified as critical or strategic raw materials
   - Demonstrate how results improve exploration, extraction efficiency, or resource availability
   - Include pathways to support EU-based mining or partnerships
2. Sustainability and Environmental Performance
   - Integrate life cycle assessment (LCA)
   - Develop low-impact mining technologies
   - Include waste valorisation or recovery from tailings
   - Address energy efficiency and carbon footprint reduction
3. Circularity and Resource Efficiency. The projects must perform research on (i) secondary resource recovery (urban mining, tailings) and (ii) design for recyclability.
4. ESG Compliance and Responsible Mining Practices. Project must include (i) stakeholder engagement plans, (ii) social impact assessment, and (iii) responsible sourcing frameworks (e.g., certification schemes like IRMA).
5. Risk Assessment and Supply Chain Resilience. The CRMA requires proactive supply-chain risk management. Projects should include (i) risk assessment methodology, (ii) scenario analysis (e.g., supply disruption), and (iii) strategies for diversification or substitution.
6. Scalability and Industrial Readiness. Mining projects are expected to contribute to real industrial capacity. Priority is given to “Strategic Projects” that demonstrate (i) Technology readiness level progression, (ii) pathway to industrial implementation, and (iii) cost and feasibility analysis.
7. Permitting, Governance, and Regulatory Alignment. CRMA introduces streamlined permitting but requires strong compliance. Projects must include (i) regulatory analysis, (ii) environmental impact assessment considerations, and (iii) plan for permitting and approvals.
8. Innovation and Strategic Value. Projects should clearly support EU strategic priorities that enable (i) green transition (renewables, batteries), (ii) digital technologies, and (iii) strategic industries (e.g., defence, aerospace).

2.6.2. Circular Economy Action Plan (CEAP 2020)

To be aligned with the Circular Economy Action Plan (CEAP 2020), projects should adopt a full life-cycle perspective and demonstrate how it contributes to keeping materials in circulation for as long as possible. Collectively, the requirements redefine mining as a circularity-compatible activity, where operational performance is evaluated not only by extraction output, but by the ability to support closed-loop material cycles, minimise environmental impacts, and integrate into EU-wide circular value chains. The requirements include:

1. Whole Life-Cycle Approach (material traceability and lifecycle data integration). The CEAP requires that circularity is addressed across the entire life cycle of materials and products, from Extraction to End-of-Life. For mining projects, projects should (i) go beyond extraction: include processing, reuse, recycling, and recovery and (ii) demonstrate how mined materials remain in circulation.
2. Resource Efficiency and Reduced Primary Extraction Pressure. A central goal is decoupling economic growth from resource use and reducing dependence on virgin materials. This implies that projects should (i) develop high-efficiency extraction technologies, (ii) improve ore recovery rates, and (iii) minimise losses along the mining value chain.
3. Waste Prevention and Valorisation. The CEAP prioritises preventing waste and turning waste into resources. Projects should include (i) recovery of valuable materials from tailings and waste rock, (ii) reprocessing of legacy mining waste, and (iii) zero-waste or low-waste mining concepts.
4. Circular Design and Use of Secondary Raw Materials. The CEAP emphasizes designing systems that enable circular flows. Projects should demonstrate (i) integration of recycled or secondary inputs and (ii) compatibility of mined materials with circular value chains (e.g., recyclability in downstream applications).
5. Circular Production Processes. The CEAP explicitly calls for greater circularity in production systems, therefore projects should develop (i) low-impact processing techniques, (ii) closed-loop water and material systems, and (iii) energy-efficient extraction and beneficiation.
6. Environmental Sustainability and Climate Alignment. Circular economy policies are closely linked to climate neutrality and biodiversity protection. Projects should include (i) Life Cycle Assessment (LCA), (ii) carbon footprint analysis, and (iii) measures to protect ecosystems and reduce land impact.
7. Development of Secondary Raw Materials Markets. CEAP promotes economic systems that enable reuse and recycling. The projects must ensure (i) quality and consistency of recovered materials, (ii) integration with downstream industries, and (iii) data transparency (e.g., digital product/material passports where relevant).
8. Innovation and New Circular Business Models. The CEAP highlights the role of research, innovation, and digitalisation. The projects must include (i) innovative technologies (e.g., AI for resource efficiency), (ii) collaboration across sectors (mining + manufacturing + recycling), and (iii) circular business models (e.g., resource recovery services).
9. Contribution to Strategic Value Chains. The CEAP focuses on resource-intensive sectors such as construction, batteries, and electronics. Projects must (i) link the mining project to critical materials for energy, mobility, digital technologies, and (ii) demonstrate contribution to sustainable industrial value chains.

2.6.3. Materials 2030 Roadmap

To align with the Materials 2030 Roadmap (Advanced Materials Initiative 2030), projects should go beyond raw material extraction and contribute to a systemic, sustainable, and innovation-driven materials ecosystem that supports the EU's green and digital transitions. The key requirements and expectations relevant for mining-focused research are:

1. Systemic Value-Chain Approach. The roadmap emphasises a full materials ecosystem perspective, connecting upstream (mining) with downstream applications. Implication for mining projects: (i) Link extraction to materials performance and applications; Demonstrate how mining outputs enable advanced materials and technologies.
2. Safe and Sustainable by Design. A core requirement is the development of safe and sustainable materials throughout their life cycle. The project must include (i) Life Cycle Assessment (LCA), (ii) environmental and health impact assessment, and (iii) design approaches that enable recyclability and reuse.
3. Circularity and Resource Efficiency. The roadmap aligns strongly with circular economy principles. Project must integrate (i) recovery from mining waste, tailings, and by-products and (ii) resource-efficient extraction (high yield, low waste), while showing contribution to circular material flows.
4. Digitalisation and Data-Driven Materials Development. A major pillar is the integration of digital tools into material development. Project must include (i) digital approaches for exploration or process optimisation, (ii) materials data sharing and documentation, and (iii) predictive models for resource quality or processing.
5. Innovation in Processing and Scale-Up. The roadmap highlights the need for new processing technologies and rapid scale-up. Project must develop (i) low-carbon extraction or beneficiation methods and (ii) scalable processes for industrial implementation, while addressing Technology Readiness Levels (TRLs) and scalability.
6. Contribution to Strategic Innovation Markets. The roadmap defines priority "materials innovation markets" (e.g., energy, mobility, construction, electronics). Projects should (i) clearly connect mined materials to batteries, renewables, electronics, or advanced infrastructure and (ii) show impact on strategic sectors and EU competitiveness.
7. Decarbonisation and Environmental Performance. Materials innovation must support climate neutrality and reduced environmental impact. Project must include (i) CO_2 reduction strategies, (ii) energy efficiency improvements, and (iii) sustainable land and resource management.
8. Standardisation, Regulation, and Data Transparency. The roadmap highlights the need for harmonised standards and regulatory alignment. Projects must ensure (i) data interoperability and traceability and (ii) compliance with EU regulations (e.g., sustainability, safety).
9. Collaboration and Ecosystem Building. The roadmap stresses strong collaboration across stakeholders. Projects should include (i) multi-actor consortia, (ii) engagement with industry and end users, and (iii) knowledge sharing and training.
10. Skills, Innovation Uptake, and Societal Engagement. The roadmap includes human and societal dimensions. Projects should consider (i) training of researchers and engineers and (ii) communication with stakeholders and society.

2.6.4. Chemicals Strategy for Sustainability (CSS 2020)

To be aligned with the EU Chemicals Strategy for Sustainability (CSS, 2020), projects should ensure that all materials, substances, and processes are safe, sustainable, and minimised in terms of harmful impacts on human health and the environment, while supporting the EU's ambition for a toxic-free, circular economy. The requirements redefine mining operations as chemically managed systems, where performance is determined not only by extraction efficiency but by the ability to minimise chemical risks, eliminate pollution pathways, and enable safe material cycles across the full lifecycle of resources. Key requirements and expectations include:

1. Safe and Sustainable-by-Design Principle. The core requirement of the CSS is that chemicals and materials must be "safe and sustainable by design" throughout their entire life cycle. Projects must (i) select and process materials with low inherent toxicity, (ii) integrate safety considerations already at exploration and extraction stages, and (iii) consider downstream impacts (e.g., processing, use, disposal).
2. Reduction and Substitution of Hazardous Substances. The CSS promotes minimising and phasing out harmful chemicals, especially those of high concern. Project should avoid or replace (i) toxic reagents (e.g., in mineral processing) and (ii) persistent, bioaccumulative, or endocrine-disrupting substances, while developing alternative, greener extraction and processing methods.
3. Zero-Pollution and Environmental Protection. The CSS is part of the EU's zero-pollution ambition. Project should include (i) pollution prevention strategies, (ii) closed-loop or low-emission processes, and (iii) monitoring and mitigation of chemical releases.
4. Life Cycle and Circularity Integration. The CSS is closely linked to circular economy goals. Project should combine mining with (i) recovery of materials from waste streams, and (ii) safe recycling of materials containing chemicals, while ensuring that recycled materials remain non-toxic and safe.
5. Improved Risk Assessment and Chemical Transparency. The CSS calls for more effective and transparent hazard and risk assessment. Project should include (i) comprehensive chemical risk assessments, (ii) evaluation of cumulative effects of multiple substances, and (iii) transparent reporting of chemical use and impacts.
6. Innovation in Safe Chemical Alternatives. The strategy strongly promotes innovation in safer chemicals and processes. Projects should develop (i) non-toxic extraction technologies (e.g., alternatives to cyanide-based processes, and (ii) bio-based or low-impact reagents, while positioning the project as contributing to next-generation sustainable materials.
7. Protection of Human Health (Workforce and Society). A central goal is to protect human health from exposure to hazardous chemicals. Projects should include (i) occupational safety measures, (ii) exposure reduction strategies, and (iii) health risk assessments.
8. Alignment with Regulatory Frameworks (REACH, CLP). The CSS builds on and strengthens EU chemical legislation. Projects should ensure (i) full regulatory compliance and (ii) proper classification, documentation, and safe handling of chemicals.
9. Contribution to Sustainable and Resilient Chemical Supply Chains. The strategy also aims to ensure secure and sustainable supply of critical chemicals. Projects should demonstrate (i) responsible sourcing of chemical inputs and (ii) reduced dependency on hazardous or scarce chemicals, while linking mining outputs to safe downstream chemical applications.

2.6.5. Zero Pollution Action Plan (May 2021)

To align with the EU Zero Pollution Action Plan (May 2021), projects should demonstrate a contribution to preventing, reducing, monitoring, and remediating pollution across air, water, soil, and ecosystems, in line with the EU's ambition to achieve a toxic-free environment by 2050. The requirements redefine mining as a multi-dimensional environmental management system, where operational performance is determined not only by resource recovery but by the capacity to minimise pollution across all environmental compartments and lifecycle stages, in alignment with the EU's transition toward a toxic-free and sustainable economy. Key requirements and expectations include:

1. Pollution Prevention at Source (Core Principle). The Action Plan prioritises preventing pollution at its origin, rather than treating it after release. Projects should design processes that (i) avoid emissions (e.g., dust, chemicals, wastewater) and (ii) use cleaner extraction and processing technologies, while prioritising low-emission mining approaches.
2. Reduction of Air Pollution. The plan sets specific 2030 targets for air quality. Projects must minimise emissions of (i) particulate matter (dust from mining operations) and (ii) NOx, SOx, and other pollutants, while including air quality monitoring systems and dust suppression and emission control technologies.
3. Protection of Water Resources. The plan targets significant reductions in water pollution, including plastic and waste. Projects should prevent contamination of groundwater and surface water by implementing (i) closed-loop water systems, (ii) wastewater treatment and reuse, and (iii) prevention of tailings leakage and acid mine drainage.
4. Soil Protection and Land Restoration. The Action Plan addresses soil pollution and degradation, and projects should minimise soil contamination from chemicals and heavy metals through (i) land restoration and rehabilitation strategies, and (ii) sustainable waste disposal and tailings management.
5. Waste Reduction and Resource Efficiency. The plan promotes waste prevention and reduced material losses. Project should develop (i) low-waste or zero-waste mining approaches and (ii) recovery of valuable materials from waste streams, while integrating with circular economy principles.
6. Reduction of Chemical Pollution. The plan aligns closely with the Chemicals Strategy for Sustainability. Projects should use non-toxic or less hazardous reagents and include (i) chemical risk assessment, and (ii) measures to avoid contamination from processing chemicals.
7. Monitoring, Data, and Digitalisation. The Action Plan emphasises monitoring and reporting systems. Projects should implement (i) real-time monitoring of emissions and pollutants, and (ii) data-driven environmental management systems, while ensuring transparent reporting of environmental performance.
8. Life-Cycle and Cross-Sector Approach. The plan promotes a holistic approach to pollution across the entire value chain. Projects should (i) consider environmental impacts beyond extraction (processing, transport, use) and (ii) integrate with circular economy and sustainable materials strategies.
9. Protection of Human Health and Ecosystems. Projects should include (i) health risk assessments (workers and communities) and (ii) biodiversity protection measures, while demonstrating reduced ecological impact.
10. Compliance, Enforcement, and "Polluter Pays" Principle. The plan emphasises strong implementation of environmental legislation. Projects should ensure (i) full compliance with EU environmental laws and (ii) internalisation of environmental costs, while planning for environmental liability and risk mitigation.

3

Approaches and implementation in DINAMINE – regulatory landscape

3.1. Environment, energy, and operations standards in the mining sector

DINAMINE focused on three domains: environment, energy and operations. The relationship between environment, energy, and operations in the mining sector is a critical, interdependent triad where operations drive heavy energy consumption, which in turn has significant environmental impacts. An example is the decline of high-grade ores, where operations require more energy-intensive extraction (more hauling, blasting, processing), creating a “paradox” where the industry needs more energy to produce the minerals necessary for a low-carbon transition.

It is not feasible to separate this triple-aspect relationship into distinct components, as none can function independently. Inevitably, the three aspects overlap and interact. To illustrate this integrated and interdependent system, Table 1 provides a representative example, while the following section presents a detailed breakdown of the standards associated with each aspect within DINAMINE.

Table 1. Relationship between environment, energy and operation standards frameworks.

Domain	Relationship with other domains
Operations	Driven by demand for resources, deep or waste-heavy mining results in environmental disturbance and waste production, and high amounts of energy use.
Energy	Mostly fossil-fuel-based, driving the high carbon footprint, yet enabling the production of materials.
Environment	Constrains operations through regulation, suffers from high-energy usage, but requires minerals from mining for the green energy transition.

3.2. Specific standards relevant to the DINAMINE technologies

The range of standards within the mining sector—encompassing environmental, operational, and energy aspects—is too extensive to be fully addressed within a single project. However, examining them in a structured breakdown can provide a clearer understanding of their scope and relevance. The full list of Standards is included in the Annex. The following standards have been selected as most relevant within the context of DINAMINE.

3.2.1. The key ISO Standards relevant within the Environmental aspects:

- ISO 14000 Family (General): These standards support life cycle assessment (LCA), helping operators analyse input/output flows, including waste disposal at the end of the chain.
- ISO 14040:2006 (Life Cycle Assessment – LCA - Principles & Framework): Used to quantify environmental impacts throughout the mining process (exploration to closure). Defines the foundational structure and principles of LCA, including how to define the goal, scope, and limitations.
- ISO 14044:2006 (Requirements & Guidelines): Specifies the detailed requirements for conducting LCA, including methodology for inventory analysis and impact assessment.
- ISO 14064 (Greenhouse Gas Accounting): Addresses climate change and its impacts. offers specifications for reporting GHG emissions and removals.
- ISO 14067:2018 (Carbon Footprint of Products): Sets standards for air quality in mining environments, particularly in cabs of equipment. Focuses specifically on quantifying greenhouse gas emissions in product life cycles.
- Key ISO Standards for Mining Waste Management:
  - ISO/AWI 25412 (Finding value in mining wastes): Currently under development, this standard focuses on characterising waste streams to recover materials and enhance economic value.
  - ISO 21795 Series: Mine Closure and Reclamation Planning: Published in 2022, this standard addresses the long-term stability of disposal facilities, which is a key objective of the Mining Waste Directive. It provides guidelines for assessment during the post-operational phase, including the management of mining legacies.
  - EN 15875:2011: Characterization of waste - Static test for determination of acid potential and neutralization potential of sulfidic waste.
  - CEN/TR 16363:2012: Characterization of waste - Kinetic testing for assessing acid generation potential of sulfidic waste from extractive industries.
  - CEN/TR 16376:2012: Characterization of waste - Overall guidance document for characterization of waste from extractive industries.
  - CEN/TS 16229:2011: Characterization of waste - Sampling and analysis of weak acid dissociable cyanide discharged into tailings ponds.
  - CEN/TR 16365:2012: Characterization of waste - Sampling of waste from extractive industries.
- ISO 50001 (Energy Management): Used to optimize energy consumption and reduce operational costs, aligning with decarbonization goals.

3.2.2. The key ISO Standards relevant within the Operations aspects:

- ISO 14001 (Environmental Management)
- ISO 14224 (Data Collection): Adapted to provide a standardized framework for capturing equipment reliability and maintenance data.
- ISO 27001 (Information Security): This is an international framework for managing information security,

protecting both traditional IT and crucial Operational Technology (OT) from cyber threats. It ensures the confidentiality, integrity, and availability of data, mitigating risks of operational disruption, theft of intellectual property, and safety breaches in increasingly automated and digitized mining environments.

- ➤ Closure and abandonment and Surface Stability: Safe procedures for closing, suspending, or abandoning mines. As of early 2026, the ISO has established specific standards for mine closure, reclamation, and management of legacy sites through its Technical Committee ISO/TC 82/SC 7 (Mine closure and reclamation management).
  - ISO/DIS 20305 (Mine Closure/Reclamation - formerly ISO/DIS 20305): Provides standardized terminology for mine closure and reclamation planning to avoid ambiguity between developers, governments, and local residents; and to ensure consistent understanding across different jurisdictions and projects.
  - ISO 21795:2022 (Mine Closure and Reclamation Planning): Published in 2021/2022, this series provides a framework for new and operating mines to plan for closure throughout the mine life cycle; it focuses on the long-term stabilization of mine sites after operations, including tailings management. Part 1-Requirements: Specifies requirements for mine closure planning, including stakeholder engagement, financial assurance, and technical procedures. Part 2 – Guidance: Provides guidance on implementing the requirements, covering land reclamation, water management, and social aspects.
  - ISO 24419-Part 1: (Mine closure and reclamation – Managing mining legacies): Deals with the ongoing stabilization and rehabilitation of land, including restoring soil and managing slope stability to minimize environmental damage. ISO 24419-Part 2: This series (published around late 2023/2026) deals with orphaned, abandoned, or legacy mines where responsibility is often unclear, focusing on transforming negative impacts into beneficial outcomes.
  - ISO/CD 8238 (Under development): Focuses on the social aspects of sustainable mining and mine closure.
  - ISO 31000: Used for risk management in the context of closure.

3.2.3. The key ISO Standards relevant within the Energy aspects:

- ➤ ISO 14040 & ISO 14044 (Life Cycle Assessment - LCA): These standards guide the evaluation of energy consumption and environmental impact across the entire mining life cycle, from exploration to closure.
- ➤ ISO 14064:2018 (Greenhouse Gas Accounting)

3.3. Alignment of DINAMINE with regulations, standards and frameworks

Table 2 lists the main DINAMINE technology modules and maps their relevance to established regulations, or standards and guidelines, where possible. The regulations are listed by topic (numbered), as described in Section 2.6.

Table 2. Standards, and guidelines related to environmental, operation and energy aspects.

DINAMINE Module	Regulations and mapped environmental standards/guidelines/resolution
Data storage	**Regulations** **CRMA** 6. Scalability and Industrial Readiness 8. Innovation and Strategic Value **CEAP** 8. Innovation and New Circular Business Models **Materials 2030 Roadmap** 4. Digitalisation and Data-Driven Materials Development 9. Collaboration and Ecosystem Building 10. Skills, Innovation Uptake, and Societal Engagement **Zero Pollution Action Plan** 7. Monitoring, Data, and Digitalisation
	Environmental standards/guideline/resolution • ISO/IEC 27001 • ISO 14224 (Data Collection)
Dashboards and Analytics (LCA-see LCA module)	**Regulations** **CRMA** 6. Scalability and Industrial Readiness 7. Permitting, Governance, and Regulatory Alignment 8. Innovation and Strategic Value **CEAP** 8. Innovation and New Circular Business Models **Materials 2030 Roadmap** 4. Digitalisation and Data-Driven Materials Development **CSS** 4. Life Cycle and Circularity Integration **Zero Pollution Action Plan** 7. Monitoring, Data, and Digitalisation
Short-term and Long-term Analytics	**CRMA** 6. Scalability and Industrial Readiness 8. Innovation and Strategic Value **CEAP** 2. Resource Efficiency and Reduced Primary Extraction Pressure 8. Innovation and New Circular Business Models **Materials 2030 Roadmap** 4. Digitalisation and Data-Driven Materials Development

DINAMINE Module	Regulations and mapped environmental standards/guidelines/resolution
Mineral Processing Model (MPM)	**Regulations** **CRMA** 2. Sustainability and Environmental Performance 6. Scalability and Industrial Readiness 7. Permitting, Governance, and Regulatory Alignment 8. Innovation and Strategic Value **CEAP** 3. Waste Prevention and Valorisation 5. Circular Production Processes 6. Environmental Sustainability and Climate Alignment 8. Innovation and New Circular Business Models **Materials 2030 Roadmap** 2. Safe and Sustainable by Design 3. Circularity and Resource Efficiency 7. Decarbonisation and Environmental Performance 8. Standardisation, Regulation, and Data Transparency **CSS** 4. Life Cycle and Circularity Integration **Zero Pollution Action Plan** 1. Pollution Prevention at Source 7. Monitoring, Data, and Digitalisation
	Environmental standards/guideline/resolution • ISO 14067:2018 - Carbon Footprint of Products • ISO 14064 - GHG Protocol • PAS 2050:2011 - the British Standards Institution – GHG • ISO 50001 (Energy Management)
Mine Information Model (MIM)	**Regulations** **CRMA** 6. Scalability and Industrial Readiness 7. Permitting, Governance, and Regulatory Alignment 8. Innovation and Strategic Value **CEAP** 2. Resource Efficiency and Reduced Primary Extraction Pressure **Materials 2030 Roadmap** 2. Safe and Sustainable by Design 3. Circularity and Resource Efficiency

DINAMINE Module	Regulations and mapped environmental standards/guidelines/resolution
Tailing Information Model (TIM)	**CRMA** 2. Sustainability and Environmental Performance 6. Scalability and Industrial Readiness 7. Permitting, Governance, and Regulatory Alignment **CEAP** 1. Whole Life-Cycle Approach 2. Resource Efficiency and Reduced Primary Extraction Pressure 6. Environmental Sustainability and Climate Alignment **Materials 2030 Roadmap** 2. Safe and Sustainable by Design 3. Circularity and Resource Efficiency 7. Decarbonisation and Environmental Performance **CSS** 4. Life Cycle and Circularity Integration **Zero Pollution Action Plan** 5. Waste Reduction and Resource Efficiency
	Environmental standards/guideline/resolution • Mining Waste Management: ISO/AWI 25412 • ISO 21795 Series • EN 15875:2011 • CEN/TR 16363:2012 • CEN/TR 16376:2012 • CEN/TS 16229:2011 • CEN/TR 16365:2012
Life Cycle Analysis (LCA)	**Regulations** **CRMA** 2. Sustainability and Environmental Performance 6. Scalability and Industrial Readiness 7. Permitting, Governance, and Regulatory Alignment 8. Innovation and Strategic Value **CEAP** 1. Whole Life-Cycle Approach 6. Environmental Sustainability and Climate Alignment 8. Innovation and New Circular Business Models **Materials 2030 Roadmap** 2. Safe and Sustainable by Design 3. Circularity and Resource Efficiency 7. Decarbonisation and Environmental Performance 8. Standardisation, Regulation, and Data Transparency **CSS** 4. Life Cycle and Circularity Integration **Zero Pollution Action Plan** 1. Pollution Prevention at Source 3. Protection of Water Resources 5. Waste Reduction and Resource Efficiency 8. Life-Cycle and Cross-Sector Approach
	Environmental standards/guideline/resolution • ISO 14001 • ISO 14040:2006 (Principles & Framework) • ISO 14044:2006 (Requirements & Guidelines)

DINAMINE Module	Regulations and mapped environmental standards/guidelines/resolution
Real-time monitoring	**Regulations** **CRMA** 2. Sustainability and Environmental Performance 6. Scalability and Industrial Readiness **CEAP** 1. Whole Life-Cycle Approach. 6. Environmental Sustainability and Climate Alignment 8. Innovation and New Circular Business Models **Materials 2030 Roadmap** 2. Safe and Sustainable by Design 3. Circularity and Resource Efficiency 7. Decarbonisation and Environmental Performance 8. Standardisation, Regulation, and Data Transparency **CSS** 4. Life Cycle and Circularity Integration **Zero Pollution Action Plan** 7. Monitoring, Data, and Digitalisation
	Environmental standards/guideline/resolution • ISO 45001 — occupational health and safety • ISO 23875 — operator-enclosure air quality
Predictive maintenance	**Regulations** **CRMA** 6. Scalability and Industrial Readiness 8. Innovation and Strategic Value **CEAP** 6. Environmental Sustainability and Climate Alignment 8. Innovation and New Circular Business Models **CSS** 4. Life Cycle and Circularity Integration
	Environmental standards/guideline/resolution • ISO 13374 — condition monitoring and diagnostics of machines • ISO 13379 — data interpretation and diagnostics techniques • ISO 17359 — general guidelines for condition monitoring • IEC 61499 — relevant for industrial automation contexts
Jumbo drill	**CRMA** 6. Scalability and Industrial Readiness 8. Innovation and Strategic Value **CEAP** 8. Innovation and New Circular Business Models
This document	**Regulations** **CRMA** 7. Permitting, Governance, and Regulatory Alignment **CSS** 8. Alignment with Regulatory Frameworks

4

Approaches and implementation in DINAMINE – technology solutions

4.1. DINAMINE – the technologies

The technological solutions developed in DINAMINE have been designed as a platform with a loosely coupled set of technologies which can be used as a fully integrated set offering a complete solution for mine sites, or can be used as a pick and choose set of tools according to the specific needs of the mine operator and its current budget availability.

The ISM-PM platform is organised in layers — interface, analytics, data space and data acquisition — complemented by a set of external-layer modules and an integration backbone.

Interface layer

- Web-based interface — visualisation of sensor data and import/export in common formats, with configurable alarms, signal smoothing and user-defined sensor groupings; a laboratory data interface with mine-tailored, easily customisable uploads and automatic de-duplication.
- Data API & access control — a REST API to set up the per-site data structure, with certificate-based authentication, per-site data isolation and user roles.

Analytics layer

- Economic Monitoring Module (EMM) — captures actual and budgeted costs, revenues, material flows and consumables, organised by department.
- Economic Insights & Reporting Module (EIRM) — interactive historical analysis of economic indicators, budget-versus-actual comparison and trend tracking.
- Economic Prognosis Module (EPM) — estimates the future economic potential of unmined blocks (block economic value, revenue forecast, cost breakdown and sensitivity analysis) to support long-term planning.
- LCA Insights & Reporting Module (LIRM) — explores and reports environmental impacts across the value chain, supporting sustainability reporting.

- Monthly report — automated aggregation of economic data for management reporting.

Data space layer

- ISM-PM Data Space — a data-agnostic central store providing secure storage and retrieval of any data type (including sensor telemetry) through a defined entity model with schema validation and per-domain isolation; supports both structured and unstructured data and loose coupling between modules.
- Data collection & management — instantiation and management of time-series data streams from sensors and other structured sources.

Data acquisition layer

- Acquisition module — ingestion of structured sensor and data-stream telemetry through standard light-weight IoT messaging and a generic broker, with schema validation, buffering/backpressure, horizontal scalability and encrypted transport.

External-layer modules

- Mine Information Model (MIM) — a block-based model of the orebody storing mass, ore quality and economic value per block at initial, predicted and measured levels, updated as geological, grade and economic data arrive.
- Tailing Information Model (TIM) — statistical classification of tailings against European and national standards into permitted, not-permitted and inconclusive, supporting environmentally compliant deposition.
- Mineral Processing Model (MPM) — a real-time model of mineral processing (feed, energy, water, waste and products) that optimises energy and resource consumption, recovery rate, tailings generation and GHG emissions.
- Active-Dig — geological boundary and discontinuity mapping, drill-rig georeferencing/navigation and blast-pattern design, using stereo-camera and LiDAR sensing.
- Active-Safe — identification of rock-fall and geotechnical stability risk in active mine areas, routed to the relevant decision-makers.
- Short-term & Long-term Analytics (SLA) — production planning over blasting rounds with task/cycle modelling and mass balance, based on statistical models built from site data.
- Smart Predictive Maintenance (PdM) — condition-monitoring-based predictive maintenance using sensor data and statistical models to detect anomalies and anticipate failures, reducing unplanned downtime; an operator dashboard presents status levels and live/historical data.
- Semi-automated drill rig integration (Jumbo drill) — a cloud-based hub exchanging drilling plans and real-time measurement-while-drilling data between the planning module, the data space and the drilling machines through secure APIs.
- Life Cycle Assessment (LCA) — real-time, cradle-to-gate environmental footprint computed from material and energy flows (foreground, background and historical data).

Cross-cutting capability

- Integration backbone — the data-agnostic data space enables loose coupling and incremental integration of any module or sensor, and the platform has been integrated and validated at the project pilot sites with real and synthetic data.

The technologies developed and implemented in the DINAMINE project can be grouped coarsely into the following categories.

Table 3. List of the DINAMINE technologies.

Technology	Database	Algorithm	Hardware	Software	Machinery
Sensors (wireless, or cabled), data loggers			x		
Chemical sensors (LIBS, XRF)			x	x	
Data exchange platform (ISM-PM)	x			x	
User interface				x	
Jumbo drill				x	x
Geological mapping system (Active-Dig)		x	x		
Real-time safety monitoring system (Active-Safe)		x	x		
Mine information model (MIM)	x	x		x	
Mineral processing model (MPM)		x			
Predictive maintenance (PdM)		x			
Life cycle analysis and impacts (LCA)	x	x			

4.2. DINAMINE – addressing identified challenges/barriers

Fourteen challenges/barriers have been consolidated from the market analysis performed as part of the project, as described below.

1. Organisational resistance to change & workflow disruption — Reliance on traditional practices creates natural resistance to change. A key concern is disruption to established workflows and the downtime associated with retrofitting brownfield operations, compounded by scepticism over the additional workload that new software may impose, and by fears of job displacement linked to autonomous technologies.
2. Skills gap & ageing workforce (the “grey tsunami”) — Anticipated retirements, low sector attractiveness to younger workers and the closure of specialised mining programmes coincide with a growing need for specialised IT skills and a steep learning curve. The skills-update process is particularly demanding for older employees, smaller operators and remote regions; industry bodies anticipate that around 20% of mining specialists are at risk of displacement or in need of reskilling.
3. “Wait-and-see” adoption posture — The high CAPEX effort slows the penetration of digital solutions, leading many SMEs to adopt a “wait-and-see” strategy. Decision-makers rarely act as front-runners, preferring proven success stories and clear economic evidence before committing.
4. Short-term decision focus & weak digitalisation strategy — Market volatility and rising operating costs push executives to prioritise short-term operational needs over long-term technology investment. This is compounded by limited executive awareness of long-term benefits and by the absence of a defined digitalisation strategy and the required skills.
5. Capital & operational intensity — Mining is inherently capital-intensive: digital tools entail substantial CAPEX for licenses, hardware and training, and an immature market makes ROI demonstration and derisking complex. Beyond CAPEX, OPEX is significant — software can be energy-intensive and reliant on cloud data transfer, and autonomous systems require costly enabling infrastructure (sensors, positioning, communication networks). A scarcity of in-house IT resources further complicates adoption.
6. Lengthy purchase cycle & commercialisation risk — The substantial capital investment lengthens the purchase cycle, with decision-making spanning months to years. A lack of in-house development competence drives SMEs toward third-party solutions, and commercialisation is exposed to compliance, scalability and continuous-support risk.
7. Data silos & legacy interoperability — “Social firewalls” between departments and sites, together with heterogeneous systems, data formats and data-ownership models, hinder effective data sharing. Integration with legacy equipment and software, and the difficulty of data migration, are recurrent obstacles to deploying new software alongside existing systems.
8. Data availability & quality — Effective modelling depends on collecting complete and historic data, which is often difficult. Data quality is further dependent on operator skill and interpretation, underlining the need for user-friendly tools, training, or interpretation provided as a service.
9. Connectivity limitations in remote/rural operations — Mining operations are frequently located in remote or rural areas where reliable internet connectivity is itself a challenge, posing problems for the integration of cloud-based solutions.
10. Cybersecurity & expanding attack surface — As operations become increasingly digitised and integrated, every connected asset increases the attack surface. Data security and compliance are major concerns in a strictly regulated sector, and the frequency and sophistication of cyber-attacks continue to rise.

11. Scalability risk — Solutions that perform well in small trials may require substantial, costly reconfiguration when scaled to full operation (for example, automation validated in open-pit settings adapted to underground conditions), so scalability risk should not be overlooked.
12. Ancillary infrastructure for the automated drill rig — An automated drill rig (Jumbo drill) requires ancillary infrastructure for efficient implementation — for example an operator cabin and reliable connectivity/communication — which, in remote areas, can be as important as the rig itself.
13. Regulatory pressure, permitting & licence to operate — Stringent environmental and safety regulation complicates permitting and the licence to operate, amplified by public opposition (NIMBYism) where mining coexists with populated areas. Smaller operators may lack the resources to meet compliance demands, while autonomous and automated equipment introduces additional regulatory considerations and growing pressure for transparent environmental and safety reporting.
14. Mining-operations uniqueness & customisation cost — Diverse data needs across departments and across mines (varying by location, magnitude and resource type) make "one-size-fits-all" software unattractive, while customisation is tedious and costly for both provider and operator.

4.3 Challenge/Barrier-to-solution mapping

The selected challenges/barriers identified in the project and listed in Section 1 have been analysed to identify how the DINAMINE technological solutions contribute to support such challenges/barriers. The table maps each challenge/barrier to the ISM-PM technologies that help to address it, the mechanism of help, and the coverage achieved.

Table 4. Matrix of challenges/barriers vs technology.

#	Challenge / Barrier	Mapped ISM-PM technologies	How they help	Coverage
1	Organisational resistance to change & workflow disruption	- Data Space (data-agnostic, loose coupling) - Lab interface (mine-tailored uploads, de-duplication) - EMM (routine per-department entry, auto-load of prior values) - Monthly report	Layering on existing systems via an agnostic integration layer avoids replacing legacy tools; interfaces fit current practice (file uploads, per-department forms), reducing retrofitting downtime and perceived added workload.	Workflow disruption mitigated.
2	Skills gap & ageing workforce ("grey tsunami")	- Web / LIBS / Monitoring interfaces (alarms, smoothing, sensor groups) - PdM operator dashboard (status levels, live + historical)	Low-complexity, user-facing interfaces lower the learning curve and let non-specialist operators act on data directly.	Usability eases the IT learning curve; the structural skills shortage.

#	Challenge / Barrier	Mapped ISM-PM technologies	How they help	Coverage
3	"Wait-and-see" posture / demand for proven ROI	- Full platform validated at the project pilot sites with real data; technical integration validation - EPM (block economic value, revenue forecast, sensitivity)	Demonstrated, integrated and operationally tested results supply the success-story evidence that wait-and-see adopters require; EPM quantifies economic value before commitment.	Provides demonstrated proof and ROI quantification.
4	Short-term decision focus & weak digitalisation strategy	- EPM (cumulative block economic value over block sequences) - MIM (initial/predicted/measured block model) - SLA (short + long-term analytics) - EIRM (trends) - LCA / LIRM (long-term footprint trends)	Provides executives with quantified long-horizon visibility — economic and environmental — countering short-termism in planning decisions.	Strong long-term decision tooling.
5	Capital & operational intensity (CAPEX, OPEX/energy, enabling infrastructure, IT resources)	- MPM (energy/resource optimisation in processing) - PdM (cuts unplanned - downtime maintenance OPEX) - LCA/LIRM (energy & emissions tracking) - EPM (ROI/CAPEX justification) - Scalable, data-agnostic architecture reusing existing IoT and sensors	Reduces OPEX and energy use and quantifies ROI; loose coupling enables incremental, lower-cost deployment instead of a single and very high investment.	OPEX/energy reduction and ROI addressed; CAPEX magnitude (licenses/hardware/training) and in-house IT scarcity are possible limiting factors to be considered.
6	Lengthy purchase cycle & commercialisation risk	- EPM economic justification - Validated scalability & support architecture.	Demonstrated validation and modular deployment can shorten the economic-justification step; scalability/support architecture lowers two risk dimensions	Not covered directly by DINAMINE as it is a procurement/market dynamic (cycle length, in-house vs third-party sourcing).
7	Data silos & legacy interoperability	- ISM-PM Data Space (data-agnostic, star topology, schema validation, structured + unstructured) - Data Acquisition (generic lightweight-IoT broker, entity mapping to external IDs) - Demonstrated cross-module integration	A central agnostic layer dissolves departmental and site silos, ingests heterogeneous formats and legacy streams, and integrates any module or sensor through defined schemas.	Core purpose and demonstrated capability of DINAMINE's ISM-PM.

#	Challenge / Barrier	Mapped ISM-PM technologies	How they help	Coverage
8	Data availability & quality (historic data, operator-dependent interpretation)	- Data Space (time-series, versioned schemas, real-time + historical) - Lab interface (historical capture, de-duplication) - Monitoring (live + historical) - Acquisition-layer validation - PdM denoising - Active-Dig hybrid accuracy	Structured, validated and persistent storage of real-time and historical data; signal cleaning and schema validation improve usable quality.	Data availability strongly addressed and data quality partly mitigated. But sensor reliability/ calibration and scarce labelled historical data are issues that should be reviewed during deployment.
9	Connectivity limitations in remote/ rural operations	- Lightweight IoT messaging - Acquisition-layer buffering/backpressure and restart-without-loss - Data Space offline-backup mode - LPWAN wireless IoT loggers	Protocol and architecture tolerate intermittent, low-bandwidth links and offline operation, reducing dependence on continuous connectivity.	Resilience to unreliable links is designed in, but site-specific limitations should be explored during deployment.
10	Cybersecurity & expanding attack surface	- Certificate-based authentication; per-domain (realm) data isolation; User roles; encrypted transport; access control + schema validation - End-to-end encryption on the drill-rig data channel	Security is designed into the platform: authenticated access, tenant isolation, encryption and validation reduce the integration attack surface.	Covers the ISM-PM stack; does not extend to the mine's whole-enterprise cyber posture.
11	Scalability risk (small trial → full operation)	- Data Acquisition (horizontally scalable, replicated deployment, defined throughput) - Data Space microservice architecture - Data-agnostic expansion; validation with synthetic + real data	The architecture is built for horizontal scaling and incremental expansion from pilot to production load.	Platform/data scalability addressed; physical/operational reconfiguration across mine types (e.g. open-pit → underground field technology) is supported.
12	Ancillary infrastructure for the automated drill rig (cabin, remote communications)	- Drill-rig integration module (cloud hub, drilling plans, real-time measurement-while-drilling, APIs) — data/communication architecture only	The rig's data and communication integration is delivered; the barrier itself concerns physical site infrastructure.	Operator cabin and remote-site connectivity/ communication are physical, site-side infrastructure.

#	Challenge / Barrier	Mapped ISM-PM technologies	How they help	Coverage
13	Regulatory pressure, permitting & licence to operate	- TIM (tailings classification vs EU/national standards) - LCA / LIRM (real-time footprint + sustainability reporting) - Active-Safe (geotechnical/rock-fall safety) - MPM (GHG, energy/resource efficiency) - EMM/EIRM (consumables records)	Supports environmental and safety compliance and transparent, auditable reporting, strengthening the licence-to-operate case.	Compliance and transparent reporting strongly supported.
14	Mining-operations uniqueness & customisation cost ("one-size-fits-all")	- Data-agnostic Data Space (optional schema vs blob, versioned entity types) - Lab interface (generic, easy to customise per mine) - Monitoring (user-defined groups) - Modular loose coupling (adopt a subset of modules)	A configurable, modular, schema-flexible design lets each mine adopt and shape only the modules it needs, avoiding costly bespoke monolithic builds.	Modular, data-agnostic design directly targets heterogeneity without per-mine rebuilds.

4.4. DINAMINE – the modules

This section presents, at a high level, the functionalities of each module developed within the DINAMINE project to compose the Integrated Smart Mine Planning and Managing system (ISM-PM). Implementation-level technical details (architectures, internal algorithms, protocols, programming languages, schemas, calibration parameters, and pilot-specific data) are intentionally omitted because these represent sensitive details of the modules, some of which are reported in the project's confidential deliverables.

Each module section follows a uniform template: (i) general functionalities, summarising what the module does and the value it delivers; (ii) technical requirements, limited to infrastructure prerequisites a mine must have in place and to integration prerequisites with existing systems; (iii) purpose in DINAMINE, describing what the project demonstrated through the module; and (iv) other applications in mining and adjacent extractive operations.

4.4.1. Data storage

General functionalities

The data storage module is the central repository of the ISM-PM system. It is designed as a data-agnostic service that stores and retrieves all data produced by the analytical modules and by the sensor network deployed throughout the mining value chain. It supports both structured data (typically telemetry from sensors and outputs from analytical modules, with a defined schema validated on arrival) and unstructured data (documents, files, and larger datasets without a fixed schema).

Information is organised hierarchically. Each operating organisation (such as a mine, a processing plant, or a corporate domain) is treated as a separate logical domain, with strict data isolation: information stored in one domain cannot be viewed from another domain without the corresponding permissions. Within each domain, the storage distinguishes categories of monitored elements (for example, a category of sensor or a category of equipment), individual elements (a specific sensor installed at a given location), and the data streams that those elements produce.

Access to the storage is mediated by a dedicated service that exposes interactive views (a web-based interface to inspect deployed sensors and their measurements) and programmatic interfaces (API) that allow other modules to retrieve and post data. All access is authenticated and authorised at domain level, so that sensitive operational, environmental, and economic data remain visible only to those entitled to access them.

Technical requirements

At infrastructure level, the data storage requires hosting on a platform with sufficient capacity for continuous ingestion of sensor streams and storage of analytical outputs over the duration of the operation, together with network connectivity between the mine site and the storage location. The storage is intended to be operated as a centralised service rather than as a local component embedded in each module or sensor.

At integration level, two prerequisites apply. First, each sensor must be declared in the storage before its data can be accepted, so that the structure of its measurements is known and can be validated on arrival. Second, each analytical module that produces or consumes data must use the storage's defined interfaces and respect the schemas declared for the data streams it interacts with. Without these prerequisites, sensor data may be rejected or analytical results may not be correctly attributed to their source.

Purpose in DINAMINE

Within the project, the data storage served as the integration backbone of the ISM-PM system. It was the single point through which sensor measurements (from chemical analysers on conveyor belts, IoT environmental and geotechnical loggers, vehicle trackers, and outputs from processing-plant control systems) and module outputs (from analytical, economic, environmental, and operational modules) were collected and made accessible to one another.

The project demonstrated that a data-agnostic, schema-validated, domain-isolated storage is capable of supporting simultaneously the needs of underground and open-pit operations without requiring a separate deployment for each, and of ingesting data from a diverse set of sensor types and from analytical modules developed by different teams, provided that each declared its data structure in advance.

Other applications

Within mining and adjacent extractive operations, the same approach can support aggregates and quarrying operations, dimension-stone operations, salt and industrial-minerals operations, and underground developments such as tunnelling, where geotechnical sensors and equipment telemetry must be consolidated with planning, environmental, and economic data. More generally, any extractive operation that needs to consolidate multi-source data across geographically distributed sites can adopt this logical model.

4.4.2. Dashboards and Analytics

General functionalities

The Dashboards and Analytics module provides the user-facing interface of the ISM-PM system. It consolidates, in a single web-based dashboard, both real-time and historical views of the operation, together with dedicated analytical views for economic performance and environmental impact. Five complementary sub-modules are grouped under this section:

1. A general web-based interface, which allows users to inspect deployed sensors and their measurements, group sensors thematically, and retrieve historical and near-real-time data through interactive views.
2. The Economic Monitoring Module (EMM), which acts as the primary entry point for economic data. It collects actual and budgeted costs and revenues, material flows, product quantities, and consumables (such as diesel and explosives), entered directly by mine personnel.
3. The Economic Insights and Reporting Module (EIRM), which provides an interactive environment for analysing historical economic performance: cost breakdowns, profit margins, production efficiency, comparison of actual versus budgeted values, and trend examination over selectable time periods.
4. The Economic Prognosis Module (EPM), which estimates the future economic potential of unmined blocks, computing expected revenues, costs, and mining efficiency at block level and cumulatively for a selected block sequence, with sensitivity analysis on key economic parameters.
5. The LCA Insights and Reporting Module (LIRM), which is a dedicated view for environmental performance. It allows users to explore, analyse, and export historical results of the life-cycle assessment, tracing each impact contribution back to a piece of equipment, a process, and a section of the mining value chain.

Together, these sub-modules give operational, financial, and environmental personnel a single point from which to monitor what is happening, compare it with what was planned, and anticipate future performance.

Technical requirements

At infrastructure level, the dashboards are accessed through a standard web browser from any workstation with general network connectivity. No specialised client software is required on the mine side. The hosting platform must provide sufficient capacity for the consolidated dashboard and analytical views and must be reachable from the mine offices where personnel will use it.

At integration level, the dashboards depend on data flowing from the underlying modules: economic data from the EMM, environmental impact data from the LCA module, and operational data from the sensors and analytical modules through the data storage. Reliable, validated data flows are therefore a prerequisite. Mine personnel must also enter periodic economic and operational information manually where automated capture is not in place.

Purpose in DINAMINE

Within the project, the Dashboards and Analytics module provided a consolidated, user-facing layer over the data and analytics generated by the rest of the system. It demonstrated that financial tracking, environmental reporting, and forward-looking economic planning can be presented at block level through a single interface, and that monthly aggregated reports can be produced automatically from the underlying data, reducing the time spent by operational personnel on manual reporting.

The economic sub-modules in particular showed how operational data and economic data can be combined to support assessment of past performance and anticipation of future performance along selected mining sequences.

Other applications

Within mining and adjacent extractive operations, the same dashboard and analytics approach is applicable wherever financial, operational, and environmental data need to be consolidated and compared against plans: aggregates and quarrying, dimension-stone operations, salt and industrial-minerals operations, and tailings reprocessing or secondary-resource recovery activities. The block-level economic and environmental views are particularly applicable to any operation that already uses (or could adopt) a block model for resource and reserve estimation.

4.4.3. Short-term and Long-term Analytics

General functionalities

The Short-term and Long-term Analytics module supports mine production planning over short time horizons, typically a sequence of blasting rounds. The mass associated with a single blasting round, which can correspond to one or several blocks of the mine information model, is treated as an “agglomerated mass”. For that mass, the user defines the ordered sequence of tasks required to complete the work (drilling, blasting, ventilation, loading, hauling, intermediate stockpiling, processing). Each task is broken down into cycles, with cycle time and number of cycles adapted to the type of task and to the machinery used.

The module displays the progress of planned tasks for the blasting round, together with the mass balance of the agglomerated mass: how much material is still in the muck pile, how much has been moved to a stockpile during hauling, and how much has reached the processing plant. A key feature is the ability to update both the duration and the number of cycles required for a given mass or volume on the basis of statistical models built from accumulated site data, in connection with the mine information model.

Technical requirements

At infrastructure level, the module requires connectivity to the data storage and to the mine information model. Operational data must be available either through manual entry by operators at the end of each shift or through navigation and telemetry sensors fitted to mining vehicles (positioning and engine activity).

At integration level, the module depends on a populated block model and on a defined task structure for the operation. When automated cycle updates from vehicle telemetry are not yet in place, the module operates on the basis of operator inputs at shift end; the statistical updating of cycle times relies on the accumulation of historical site data.

Purpose in DINAMINE

Within the project, the Short-term and Long-term Analytics module was developed and integrated with the mine information model. It demonstrated the principle of linking field activities back to the block model, of tracking planned-versus-actual progress for blasting rounds, and of using accumulated operational data to refine future estimates of cycle time and cycle count. In the project, current operation relies on operators entering completed cycles at the end of each shift; automatic cycle updates from on-vehicle navigation sensors were pending full sensor deployment at the time of the corresponding deliverable.

Other applications

Within mining and adjacent extractive operations, this approach can be applied to any underground or open-pit operation organised around cyclic blasting rounds, to quarrying for aggregates or dimension stone, and to tunnelling for construction. The statistical refinement of cycle times based on accumulated data is particularly relevant in operations that face variable geological conditions and therefore variable cycle durations from one round to the next.

4.4.4. Mineral Processing Model (MPM)

General functionalities

The Mineral Processing Model (MPM) is an interactive data model designed to monitor and evaluate the efficiency of the mineral processing stage in near real time. The model utilises sensor measurements related to input feed, energy consumption (both electrical and fuel-based), water consumption, mass flow, and the elemental composition of feed and products. New sensors were selected because they provide new information not previously collected at the plant. Moreover, previously intermittent or delayed measurements are supplemented with, or replaced by, real-time operational data, to support process control and improved environmental management. From these inputs, the model computes key performance indicators including total water consumption, total modelled energy consumption, mass balance, ore recovery expressed as a mass percentage of selected chemical elements, and modelled greenhouse-gas emissions associated with the processing stage, creating a dynamic and more complete picture of plant performance.

The model outputs are made available to the rest of the ISM-PM, enabling other modules to attribute recovery, energy, and emissions data to a specific shift.

Technical requirements

At infrastructure level, the MPM requires continuous data acquisition from the processing plant. Typical sensor categories used are weightometers on conveyor belts to provide data into loading conditions of the input, supporting stable handling of the input feed along with continuous visibility of throughput being aligned with the production objectives. Similarly, mass data is collected for the product and tailings. Elemental concentration analysers (LIBS sensors) are used for in-line elemental characterisation of moving input feed material to monitor chemical consistency and control of contaminant elements influencing the quality for downstream applications in end-products. This also helps the plant operators respond more effectively to ore variability and alignment with the concentrate targets. Water flow meters offer data on resource use in addition to the environmental reporting figure. Electrical power meters and energy sensors provide data across the main processing stages (crushers, mills, screens, and downstream units) helping to link the energy demand with throughput. Time-aligned measurements are required to account for the residence time of material through the plant, so that inputs and outputs can be correctly matched.

At integration level, the MPM depends on shift-based information, so that processed material can be attributed to a specific shift. The model also relies on the data storage as the channel through which sensor data are made available.

Purpose in DINAMINE

Within the project, the MPM was deployed across processing settings with different operational dynamics, including continuous and on-demand processing, and configurations with and without a tailings stream. It demonstrated that near-real-time monitoring of recovery and energy at processing-stage granularity is feasible, and that the resulting data can be fed back to the mine planning function to refine estimates of recoverable content for the rock mass.

Other applications

Within mining and adjacent extractive operations, the MPM approach is applicable to any beneficiation plant or mineral concentrator where mass and elemental balances must be tracked in real time. It is equally relevant to aggregates processing plants (crushing and screening), dimension-stone processing, and operations dedicated to the reprocessing of historical tailings and waste rocks for secondary-resource recovery.

In a broader sense, MPM with the sensor package backed by real time technologies, the mines and processing plants can shift reactive management to predictive management, enabling better operational and environmental results.

The MPM model developed using the processes and data from the DINAMINE pilot sites is transferable and may be tailored to other mine sites, processes and operations.

4.4.5. Mine Information Model (MIM)

General functionalities

The Mine Information Model is a data structure developed specifically for mining activities. It works as a unified database to store and process mining data across the whole mine value chain, from exploration through development, production, processing, and the assessment of the environmental impact of mining activities.

The model divides the mining zone into representative elemental volumes (referred to as blocks) and stores or estimates data for each block individually. For each block, three levels of data are maintained: initial data, derived from early site studies and exploration; predicted data, updated from initial data as new information becomes available; and measured data, recorded after the block has been mined. The model updates itself when new geological boundaries are identified, when new ore-grade data become available, and when new economic data are produced.

The MIM consolidates and harmonises inputs from several other modules of the system, including the mineral processing model (tonnages, recoveries, feed/product/tailings grades per block), the real-time geological mapping module (mapped boundaries and discontinuities), the tailing information model (classification of tailings linked back to the source block), and the economic modules (mining costs and revenues at block or period level).

Technical requirements

At infrastructure level, the model is deployed as a cloud-hosted database accessible through a web dashboard. Network connectivity between the mine site and the hosting environment is required for routine update of the model.

At integration level, the MIM depends on the data storage and on the modules listed above to populate and update its block-level data. It can be deployed in a standalone configuration using only exploration data and early planning assumptions, with the understanding that the quality and resolution of its outputs will improve as additional measured data accumulate.

Purpose in DINAMINE

Within the project, the MIM was developed and deployed in the cloud as the central spatial-data backbone of the ISM-PM. It demonstrated that planning, environmental, and economic decisions can be tied to specific volumes of the rock mass, that early-stage assumptions can be progressively refined as the operation advances, and that a statistical predictive capability can be applied to areas of the deposit which have not yet been mined.

Other applications

Within mining and adjacent extractive operations, the MIM is applicable to open-pit and underground mining of any commodity that uses (or could use) a block-model representation of the orebody. It is equally relevant to aggregates and dimension-stone resource estimation, to industrial-minerals and salt operations, and to underground developments where a 3D inventory of the rock mass is needed for combined geological, geotechnical, operational, and environmental purposes.

4.4.6. Tailing Information Model (TIM)

General functionalities

The Tailing Information Model records the key properties of tailings or waste rock produced from mining operations, together with where and how they are deposited. Its primary purpose is to link waste disposal with the orebody, so that mining activities can deliver better environmental and societal outcomes. The model stores chemical, mineralogical, physical, geotechnical, and spatial data over time, and updates these data as new measurements become available.

Based on those data, the TIM classifies tailings materials into three categories. “Permitted” materials can be stored in approved facilities (dumps, dams, backfill, or other deposition options, depending on the operation’s permit). “Not permitted” materials cannot be stored as-is and require treatment, for example through mixing with other materials to reduce risks such as acid drainage. “Inconclusive” materials cannot be classified with high confidence and trigger a recommendation for additional testing.

Technical requirements

At infrastructure level, the TIM is deployed in conjunction with the mine information model in a cloud-hosted environment. Determination of tailings classification requires reliable chemical-composition measurements on the tailings stream, typically through chemical analysers suitable for solid-phase analysis, together with a systematic sampling and testing programme designed in line with applicable standards.

At integration level, the TIM depends on the data storage for data exchange, on the mine information model for the link to source blocks of the orebody, and on the mineral processing model for the characterisation of the material that enters the tailings stream. The TIM cannot be operated in a fully standalone configuration: it requires real-time measurements from the processing plant to fulfil its function.

Purpose in DINAMINE

Within the project, the TIM was developed as part of the mine information model and demonstrated for the assessment of tailings against acceptance limits set by the operating permit and the applicable standards. The model supported decisions on tailings deposition by assessing the chemical composition of the solid phase against thresholds derived from the relevant standards on tailings characterisation.

Other applications

Within mining and adjacent extractive operations, the TIM is applicable to any operation that manages tailings or waste rocks: surface and underground mines depositing tailings in dams, dumps, sea or pit-fill configurations; backfilling operations; and secondary-resource recovery activities aimed at reprocessing historical tailings or waste rocks. The classification approach is equally relevant to environmental compliance reporting and to permitting of new operations.

4.4.7. Life Cycle Assessment (LCA)

General functionalities

The Life Cycle Assessment module evaluates the potential environmental impacts of mining activities on a cradle-to-gate basis. It performs the assessment dynamically, using a life-cycle inventory dataset compiled from real-time data captured by the sensors installed across the operation, complemented by background data on emissions and energy use for upstream and downstream processes that are external to the mine itself.

The module computes environmental impacts across several impact categories (for example global warming potential, water depletion potential, human toxicity potential, and others), identifies hotspots where most impact occurs, and presents results in a form that allows operational personnel to take informed decisions on-site. Results can be examined per shift, per process equipment, and per section of the mining value chain, and can be aggregated over configurable reporting periods.

Technical requirements

At infrastructure level, the LCA module requires a stable connection to the data storage in order to retrieve sensor measurements and other input data, and access to validated background datasets for the upstream and downstream processes.

At integration level, the LCA module depends on real-time sensor data for foreground inventory (energy, materials, emissions, chemical composition of water), on the economic modules for resource and material costs used in the conversion of measurements into a functional unit, and on the data storage as the data exchange channel. Results are published back through the data storage and made available through the dedicated environmental view of the dashboard.

Purpose in DINAMINE

Within the project, the LCA module demonstrated cradle-to-gate environmental assessment of mining and mineral processing activities using sensor-based primary data and a real-time life-cycle inventory. Results were produced at equipment and process level and were made available to mine operators through an interactive view, with traceability across value chains, processes, and equipment.

Other applications

Within mining and adjacent extractive operations, the LCA module is applicable to any operation that intends to track its environmental footprint dynamically rather than retrospectively, including aggregates, dimension-stone, salt and industrial-minerals operations, mineral processing plants, and secondary-resource recovery operations. The approach is particularly relevant for operations producing critical or strategic raw materials, for which environmental footprint reporting is becoming a regulatory expectation.

4.4.8. Mapping and real-time monitoring

General functionalities

The mapping and real-time monitoring capability of the ISM-PM is delivered through two complementary modules that operate on the rock surfaces in the active zone of the mine.

The first module provides real-time geological mapping of the recently exposed rock surface. It scans the surface using imaging and laser-based sensors, identifies geological boundaries and discontinuities, and uses this information to assess the geomechanical condition of the working face. The system can also propose or update the blasting pattern for the next excavation round and transmit it to the drilling equipment, supporting drilling-and-blasting optimisation block by block.

The second module is dedicated to real-time assessment of rockfall hazard in the active zone of the mine (the stope in underground operations, the active bench in open-pit operations). It compares successive scans of the rock surface to detect displacements, classifies the hazard level, and produces a spatial hazard map. The hazard map and any associated alarms are transmitted to the central system. In addition, the module can issue a local alarm at the location of the scanner if communication with the central system is disrupted.

Technical requirements

At infrastructure level, both modules require dedicated industrial-grade computing hardware on site, connected directly to the scanning equipment (stereo cameras for imaging and laser-based scanners for ranging and displacement measurement). Reliable access to the active mining zone is required, as is local power and a stable connection between scanner and processing unit. Connection to the central ISM-PM is needed for routine operation, but both modules are designed to continue operating in standalone mode if connectivity to the central system is lost.

At integration level, the geological mapping module produces inputs that are consumed by the mine information model (mapped boundaries) and by the drilling equipment (updated blasting pattern). The rockfall hazard module consumes geomechanical data produced by the geological mapping module and shares hazard outputs through the data storage.

Purpose in DINAMINE

Within the project, the geological mapping module was developed and tested over several field campaigns in underground mine settings, including its use jointly with semi-automated drilling equipment. The rockfall hazard module was demonstrated in real operating conditions, identifying scanned areas with elevated rockfall risk and the associated unstable rock geometry. Both modules were shown to operate in coordination with the central system and, where needed, in a standalone configuration.

Other applications

Within mining and adjacent extractive operations, the real-time monitoring modules are applicable to any underground or open-pit operation with active development faces, to tunnelling for construction (where similar geotechnical hazards apply), to quarry blasting and bench monitoring, and to geotechnically sensitive sites where displacements and discontinuities must be tracked continuously. The combination of geological mapping with optimised blast design is particularly relevant for selective mining of irregular orebodies and for operations seeking to minimise dilution and energy consumption in comminution.

4.4.9. Jumbo drill

General functionalities

The Jumbo Drill module entails a semi-automated drilling jumbo capable of executing the borehole pattern for drilling and blasting provided by the real-time geological mapping module. The jumbo adjusts and guides its boom according to the pattern, records Measurement-While-Drilling (MWD) data during execution, and makes those data available to the ISM-PM.

In addition to executing drilling patterns, the jumbo can receive safety alerts from the rockfall hazard monitoring module and downtime warnings from the predictive maintenance module, so that the operator is kept informed of relevant conditions during operation.

Technical requirements

At infrastructure level, the jumbo requires a reliable wireless access point at the drilling face for exchange of drilling plans and MWD data with the central system, and a stable means of positioning (surveying) of the jumbo chassis, since the accuracy of the executed pattern depends on the accuracy with which the jumbo is positioned in the local coordinate system of the working face.

At integration level, the jumbo exchanges data with the real-time geological mapping module (which provides the borehole pattern) and with the data storage (which receives the MWD data and forwards them to other modules, including the predictive maintenance module). A secure data-exchange channel between the jumbo and the central system is therefore a prerequisite.

Purpose in DINAMINE

Within the project, the semi-automated jumbo was developed and integrated with the geological mapping module. The jumbo demonstrated that the loop between real-time mapping of the rock surface, optimised blast design, and execution at the face can be closed in a single operational workflow, with MWD data continuously fed back to the ISM-PM for further use in geotechnical interpretation and for equipment maintenance.

Other applications

Within mining and adjacent extractive operations, semi-automated drilling jumbos integrated with mapping and central data systems are applicable to underground mining of any commodity, to underground bolting operations, and to tunnelling for construction. The MWD data they produce are valuable for any operation that uses the drilling process itself as a source of geotechnical or productivity information.

4.4.10. Predictive maintenance

General functionalities

Predictive maintenance continuously monitors data delivered by sensors on and around mining equipment being used in live operational conditions. Using an integrated analysis of live sensor data, historical trends in the data, and data on environmental conditions, Predictive Maintenance can identify signs of wear, reduced performance or imminent malfunctioning, and alert operators of potential problems and/or the need to carry out maintenance. This can contribute significantly to reducing unplanned downtime, optimising maintenance schedules, and extending equipment lifespan.

Two analytical paradigms are supported. *Condition Monitoring* augments traditional alarm systems (which raise alarms when parameter values are detected outside a defined "safe" range) with trend analyses and predictive elements based on physical and operational knowledge of the equipment, applied to measurements gathered over time. *Machine Learning* can be applied where sufficiently large data volumes have been accumulated over time to allow models to be trained on patterns of normal and abnormal operation. Machine learning makes it feasible to detect anomalies based on patterns arising from *combinations* of parameters that might not have been recognised by equipment operators. The choice between the two is driven by the nature of the equipment being monitored, the failure modes targeted, and the availability of sufficient volumes of training data. In DINAMINE, our work was based on Condition Monitoring as it was not feasible within the time available to gather enough data to allow training of a Machine Learning model.

Technical requirements

At the infrastructure level, Predictive Maintenance requires deployment of sensors on the target equipment. Sensor categories typically include 3D vibration sensors, pressure sensors, temperature sensors, and oil-pressure sensors, selected in dialogue with the equipment owner and adapted to the failure modes being targeted. Reliable sensor placement and calibration, together with reliable data connectivity between the equipment and the central system, are essential.

At the integration level, Predictive Maintenance needs reliable data storage to act as the channel through which large volumes of sensor data are made available, and on access to the maintenance schedule recommended by the equipment manufacturer and to historical maintenance records. Effective Predictive Maintenance also depends on sufficient observations over time: condition-monitoring techniques require enough operating hours to fine-tune analysis algorithms, and machine-learning techniques require even larger volumes of operational data to train models.

Purpose in DINAMINE

Within the project, Predictive Maintenance was applied to two categories of equipment selected jointly with industrial partners: an underground drilling machine (the "Jumbo drill" described above) and a piece of comminution equipment (known as a "conical crusher") in a processing plant. The work focused on key components of those machines, on the identification of failure modes that could be detected through sensor data, and on the construction and refinement of detection models. The activity demonstrated the feasibility of detecting precursors of catastrophic failures of high-value components on the basis of routine operational data, while also illustrating the practical challenges associated with sensor placement, calibration, and the accumulation of sufficient operational data.

Other applications

Within mining and adjacent extractive operations, the Predictive Maintenance approach is applicable to any heavy equipment whose unplanned downtime represents a significant operational and financial risk. Examples would include: drilling and bolting equipment, primary, secondary, and tertiary comminution equipment, screens, mobile haulage equipment, and conveyor systems. The same approach is equally relevant in quarrying and aggregates, in tunnelling, and in mineral processing more generally.

The Predictive Maintenance (PdM) work in DINAMINE clearly illustrated the significant potential of PdM for avoiding costly unscheduled downtime by predicting the need for maintenance interventions or changes in operating parameters to prevent equipment failure. Clearly, the full potential can only be achieved if PdM is applied on a wide scale to multiple pieces of equipment, rather than to just one per site as in DINAMINE. Some key lessons learned from experiences in DINAMINE that can be useful to organisations planning to apply PdM on a wide scale are as follows: (a) It is best to start with a limited number of critical equipment cases where failure modes and maintenance priorities can be clearly defined, and where some operational data has already been gathered; (b) Domain expertise is essential for selecting meaningful failure modes and interpreting sensor values to avoiding creating models that do not accurately reflect actual equipment behaviour; (c) Sensor reliability, placement and calibration is critical. Poor sensor quality or unstable connectivity can delay model development and reduce confidence in model outputs; (d) Historical data infrastructure is as important as real-time data collection. Sensor values must be transmitted, stored and made available in a structured way over sufficiently long periods to support model development, benchmarking and later validation; (e) Labelled historical failure and maintenance events can be a limiting factor for PdM. Without such events, it is difficult to train and validate models that predict failures rather than only detect abnormal behaviour; (f) Machine Learning models can support advanced anomaly detection and prediction, but only when sufficient and representative data are available; (g) Operator-facing interfaces are important. PdM outputs must be presented in a way that supports maintenance decisions, for example through status levels, anomaly events and access to both live and historical sensor data.

5 Related HORIZON projects

The following matrix presents a comparative overview of related HORIZON-funded research and innovation projects, the main focus areas and challenges addressed, and synergies with DINAMINE. The purpose of this analysis is to identify complementarities, common barriers, and potential lessons learned that can support the implementation of digital and sustainable mining solutions within European mining operations and future research and innovation initiatives.

Table 5. Comparative list of HORIZON-funded projects related to DINAMINE.

Project acronym	Main focus areas	Key challenges addressed	Synergies with DINAMINE
MINE.IO	Holistic digital mining ecosystem integrating IoT, digital twins, AI, predictive maintenance, and interoperable mine management systems	Interoperability, fragmented data, predictive maintenance, cybersecurity, digital integration, operational optimisation	Very high relevance due to its focus on integrated digital mine ecosystems and interoperability frameworks similar to ISM-PM
MASTERMINE	Standardisation, digital transformation governance, innovation management, workforce transition, and sustainable mining practices	Standardisation gaps, organisational resistance, workforce readiness, regulatory alignment, innovation uptake	Strong relevance for compliant-by-design strategies and standardisation monitoring activities
DIG_IT	IoT-enabled mining operations, real-time monitoring, environmental monitoring, and predictive analytics	Real-time monitoring, safety, environmental compliance, operational optimisation, predictive analytics	Strong methodological relevance for environmental and operational monitoring systems
illuMINEation	Industrial IoT, predictive maintenance, large-scale data handling, and digital mine monitoring	Predictive maintenance, IoT deployment, operational data management, equipment monitoring	Relevant for predictive maintenance and industrial digitalisation strategies

NEXGEN-SIMS	Autonomous, battery-electric, and connected mining systems integrated with 5G-connected environments	Automation, electrification, safety, connectivity, sustainability, remote operations	Highly relevant for automation and future autonomous mining ecosystems
ROBOMINERS	Bio-inspired robotic mining systems for difficult and hazardous environments	Autonomous mining, remote operations, safety risks, inaccessible mining areas	Relevant for autonomous operations and advanced robotic mining approaches
DigiEcoQuarry	Sustainable digital transformation and environmental optimisation in mining and quarrying	ESG compliance, environmental impact reduction, digital monitoring, sustainability	Strong relevance for ESG-oriented mining digitalisation
MultiMiner	Machine learning and Earth Observation tools for raw materials exploration and mining intelligence	Resource exploration complexity, data analytics, AI integration, strategic planning	Relevant for AI-supported mining intelligence and exploration optimisation
PERSEPHONE	Autonomous technologies for deep and abandoned mines	Deep mining safety, remote operations, hazardous environments, automation	Relevant for remote and autonomous operations in complex underground conditions

5.1. Comparative Analysis

The analysis of the most relevant EU-funded projects demonstrates that the European mining innovation ecosystem is converging around several strategic priorities: interoperability, automation, ESG compliance, predictive maintenance, operational safety, and sustainable digital transformation.

Among these projects, MINE.IO shows the highest level of alignment with DINAMINE due to its focus on integrated digital ecosystems, IoT interoperability, predictive maintenance, and mine-wide data integration. MASTERMINE contributes strongly from a governance and standardisation perspective, particularly in relation to workforce readiness and alignment with emerging industrial standards. DIG_IT and illuMINEation provide important lessons regarding real-time monitoring, IoT deployment, and predictive operational analytics.

Projects such as NEXGEN-SIMS, ROBOMINERS, and PERSEPHONE demonstrate the broader European trend toward automation, autonomous systems, and remote mining operations, particularly in hazardous or deep underground environments. Meanwhile, DigiEcoQuarry and MultiMiner highlight the increasing importance of sustainability, AI-supported exploration, and environmentally optimised mining practices.

The analysis of projects reveals several cross-cutting challenges and best practices relevant to the implementation of digital mining solutions:

- **Standardisation engagement:** Projects such as MASTERMINE demonstrate the value of continuous engagement with standardisation bodies and technical committees, ensuring that innovative solutions remain aligned with emerging industry standards.
- **Interoperability and data exchange:** Digital mining solutions require common communication protocols and interoperable data systems, as highlighted by MINE.IO's use of IoT standards and predictive maintenance frameworks.
- **Cybersecurity and data governance:** The increasing reliance on digital platforms and real-time data analytics requires robust cybersecurity standards, including frameworks such as ISO/IEC 27001.

- **Sustainability and energy efficiency:** Environmental and energy management standards (e.g., ISO 14001 and ISO 50001) are essential for supporting the transition toward sustainable and low-carbon mining operations.
- **Emerging technologies:** New technologies such as wireless charging, electrification of mining equipment, and blockchain-based data systems may play an important role in the future digital mining ecosystem.

A common conclusion emerging from all projects is that successful digital transformation in mining requires more than technological innovation alone. Effective adoption depends equally on interoperability, cybersecurity, workforce adaptation, regulatory alignment, scalability, and the ability to demonstrate measurable operational and environmental benefits. These lessons strongly reinforce the strategic direction adopted within DINAMINE and support the development of modular, interoperable, and compliant-by-design digital mining solutions tailored to European mining operations.

ANNEX

The key ISO Standards relevant within the Environmental aspects

- ISO 14000 Family (General): These standards support life cycle assessment (LCA), helping operators analyse input/output flows, including waste disposal at the end of the chain.
- ISO 14001:2015 (Environmental Management System - EMS): This is the primary standard used to comply with the directive's requirements to prevent or reduce environmental impacts. It mandates a "Plan-Do-Check-Act" cycle, ensuring regular, systematic assessment of waste disposal processes, pollution reduction, and management of waste heaps and tailings ponds. It is widely used to demonstrate commitment to Best Available Techniques (BAT).
- ISO 14015: Environmental Assessment of Sites and Organizations: Used to conduct environmental assessments (site investigations) during the operational phase.
- ISO 14040:2006 (Life Cycle Assessment – LCA - Principles & Framework): Used to quantify environmental impacts throughout the mining process (exploration to closure). Defines the foundational structure and principles of LCA, including how to define the goal, scope, and limitations.
- ISO 14044:2006 (Requirements & Guidelines): Specifies the detailed requirements for conducting LCA, including methodology for inventory analysis and impact assessment.
- ISO 14046:2014 (Water Footprint): Provides guidelines for assessing water-related environmental impacts.
- ISO 14064 (Greenhouse Gas Accounting): Addresses climate change and its impacts. offers specifications for reporting GHG emissions and removals.
- ISO 14067:2018 (Carbon Footprint of Products): Sets standards for air quality in mining environments, particularly in cabs of equipment. Focuses specifically on quantifying greenhouse gas emissions in product life cycles.
- ISO 19011: Guidelines for Auditing Management Systems: Ensures that the environmental controls are audited periodically.

- Key ISO Standards for Mining Waste Management:
  - ISO/AWI 25412 (Finding value in mining wastes): Currently under development, this standard focuses on characterising waste streams to recover materials and enhance economic value.
  - ISO 21795 Series: Mine Closure and Reclamation Planning: Published in 2022, this standard addresses the long-term stability of disposal facilities, which is a key objective of the Mining Waste Directive. It provides guidelines for assessment during the post-operational phase, including the management of mining legacies.
  - EN 15875:2011: Characterization of waste - Static test for determination of acid potential and neutralization potential of sulfidic waste.
  - CEN/TR 16363:2012: Characterization of waste - Kinetic testing for assessing acid generation potential of sulfidic waste from extractive industries.
  - CEN/TR 16376:2012: Characterization of waste - Overall guidance document for characterization of waste from extractive industries.
  - CEN/TS 16229:2011: Characterization of waste - Sampling and analysis of weak acid dissociable cyanide discharged into tailings ponds.
  - CEN/TR 16365:2012: Characterization of waste - Sampling of waste from extractive industries.
- ISO/AWI 25412 (Under Development): Specifically focused on finding value in mining wastes, this standard aids in assessing material characterization, waste management objectives, and potential for re-commercialization throughout the life of the mine.
- ISO 50001 (Energy Management): Used to optimize energy consumption and reduce operational costs, aligning with decarbonization goals.

The key ISO Standards relevant within the Operations aspects

- ISO 14001 (Environmental Management).
- ISO 23875:2021 (Mining - Operator enclosures - Air quality control systems and air quality performance testing): It establishes rigorous, uniform requirements for cabin air filtration, CO_2 monitoring, and positive pressure to protect workers from airborne particulate matter and hazardous gases across the life cycle of mining equipment.
- ISO 26000 (Social Responsibility): Offers guidelines for ethical behavior and transparent communication with community stakeholders to manage social impacts.
- ISO 14224 (Data Collection): Adapted to provide a standardized framework for capturing equipment reliability and maintenance data.
- ISO 27001 (Information Security): This is an international framework for managing information security, protecting both traditional IT and crucial Operational Technology (OT) from cyber threats. It ensures the confidentiality, integrity, and availability of data, mitigating risks of operational disruption, theft of intellectual property, and safety breaches in increasingly automated and digitized mining environments.
- ISO/IEC 13249-6: Specifies an interface for data mining, enabling standardized access to and manipulation of data structures for data mining activities.
- ISO 45001 (Occupational Health and Safety): Critical for managing the high-risk nature of mining, providing frameworks to reduce workplace injuries, accidents, and fatalities.
- ISO 9001 (Quality Management Systems): provides a framework for maintaining high-quality standards to help ensure consistent quality of mined products and services.

- Technical Interoperability & System Communication: Regulations concerning communication between shifts.
  - ISO 19434 (Accident Classification): Provides standardized, comprehensive language for reporting accidents and injuries, allowing for improved communication between operators and safety regulators.
  - ISO 22932-10:2025 (Haulage Vocabulary): Standardizes terms for underground and surface haulage (loading, hauling, dumping), eliminating confusion from regional terminology differences.
  - ISO 23725:2024 (Autonomous Mining Systems): This standard enables communication and interoperability between autonomous systems and fleet management systems (FMS).
  - ISO/TC 82/SC 8 (Automated Mining Systems): A committee focused on standards for automated machine safety, collision awareness, and secure high-speed mobile data communication. Specifications relating to specialized mining machinery and equipment used in opencast mines (e.g. conveyors, high wall miners, rock drill rigs and continuous surface miners) and all underground mining machinery and equipment for the extraction of solid mineral substances [e.g. road headers, continuous miners, rock drill rigs, raise boring machines, high wall miners, LHDs, mining auger boring machines, RMDSs (rapid mine development systems)]
  - ISO 45001:2018 (Clause 7.4): Focuses on establishing processes for communicating safety-critical information across all levels, ensuring two-way communication.
  - ISO 9001:2015 (Clause 6.3 & 8.1): Focuses on the "Planning of Changes" to ensure that when shifts change, the operational and quality management systems remain effective.
- Mobile plant: Key ISO standards for mobile mining plant focus on operator safety, machine integrity, and automated systems. They cover design, testing, and maintenance to minimize operational risks like fire and unplanned movement.
  - ISO 17757:2017 (Autonomous Systems): Sets safety requirements for autonomous and semi-autonomous earth-moving and mining machinery, including collision detection and system control.
  - ISO 19296:2018 (Underground Mobile Machines): Specifies safety requirements for self-propelled machines, including Load Haul Dumps (LHDs), dozers, and personnel transporters, covering braking, steering, and structural integrity.
  - ISO 20474 Series (Earth-moving Machinery Safety): Covers general safety requirements for surface mobile equipment (Parts 1-14).
  - ISO 23875:2021 (Operator Enclosure Air Quality).
  - ISO 3450:2011 (Earth-moving machinery — Wheeled or high-speed rubber-tracked machines): Specifies performance requirements and test procedures for brake systems on mobile equipment.
  - ISO 5006:2017 (Operator Visibility): Defines test methods and performance criteria for the operator's field of view on earth-moving machinery.
  - ISO 5010:2019 (Steering): Specifies steering requirements for rubber-tyred earth-moving machines.
- Ground movement: ISO standards regarding ground movement in the mining sector primarily focus on structural design for underground stability, safety of autonomous machinery navigating changing terrain, and, more recently, environmental management of stability during mine closure.
  - ISO 17757:2017 (Autonomous Systems).
  - ISO 19296:2018 (Underground Mobile Machines).
  - ISO 20474-1:2017: General safety requirements for earth-moving machinery
  - ISO 21815:2022 (Earth-moving machinery): Collision warning and avoidance. Part 1: General requirements: This standard provides the framework for detecting objects (people or other machines) and initiating automatic intervention (speed reduction or motion inhibition). Part 2 and 3: These parts

define the communication interfaces and interoperability, ensuring that proximity detection systems (PDS) from different vendors can safely communicate with the machine's control system to manage movement.

- ISO 2867:2011: Access systems.
- ISO 3449:2005: Falling-object protective structures.
- ISO 3471: Roll-overprotective structures (ROPS).
- ISO 6165:2022 - Earth-moving machinery — Basic types — Identification and vocabulary: Defines the types of machines used for transporting and spreading materials, crucial for identifying equipment covered under the safety standards.
- ISO 6393 and ISO 6395: Focus on testing and evaluating noise emissions from earth-moving machinery in mining.
- ISO/TC 127 Earth-moving machinery:
  - ISO/TC 127/SC1: Test methods relating to safety and machine performance.
  - ISO/TC 127/SC 2: Safety, ergonomics and general requirements.
  - ISO/TC 127/SC 3: Machine characteristics, electrical and electronic systems, operation and maintenance.
  - ISO/TC 127/SC 4: Terminology, commercial nomenclature, classification and ratings.

➤ Underground Structural Integrity and Loads: ISO Ground displacement loads in the mining sector refer to standardized design requirements for managing the movement of rock mass, soil, and underground structures (such as tunnels, shafts, and conveyor supports) due to excavation-induced stress, deformation, or seismic activity.

- ISO 19426 (Structures for mine shafts): This series covers safety requirements for shaft infrastructure, including headframes and shaft system structures.
- ISO 23469:2005: Focuses on seismic actions for designing geotechnical works, which includes how seismic-induced ground displacement affects underground structures.
- ISO 23872:2021 (Mining structures — Underground structures): This standard specifies design loads and procedures for steel and concrete structures used in underground mines. It includes critical guidance on: Ground displacement loads (accounting for initial relaxation, long-term deformation, and sudden displacement, and support systems (covers structures supporting loose rock and high-pressure bulkheads).

➤ Closure and abandonment and Surface Stability: Safe procedures for closing, suspending, or abandoning mines. As of early 2026, the ISO has established specific standards for mine closure, reclamation, and management of legacy sites through its Technical Committee ISO/TC 82/SC 7 (Mine closure and reclamation management).

- ISO/DIS 20305 (Mine Closure/Reclamation - formerly ISO/DIS 20305): Provides standardized terminology for mine closure and reclamation planning to avoid ambiguity between developers, governments, and local residents; and to ensure consistent understanding across different jurisdictions and projects.
- ISO 21795:2022 (Mine Closure and Reclamation Planning): Published in 2021/2022, this series provides a framework for new and operating mines to plan for closure throughout the mine life cycle; it focuses on the long-term stabilization of mine sites after operations, including tailings management. Part 1-Requirements: Specifies requirements for mine closure planning, including stakeholder engagement, financial assurance, and technical procedures. Part 2 – Guidance: Provides guidance on implementing the requirements, covering land reclamation, water management, and social aspects.

- ISO 24419-Part 1: (Mine closure and reclamation – Managing mining legacies): Deals with the ongoing stabilization and rehabilitation of land, including restoring soil and managing slope stability to minimize environmental damage. ISO 24419-Part 2: This series (published around late 2023/2026) deals with orphaned, abandoned, or legacy mines where responsibility is often unclear, focusing on transforming negative impacts into beneficial outcomes.
- ISO/CD 8238 (Under development): Focuses on the social aspects of sustainable mining and mine closure.
- ISO 31000: Used for risk management in the context of closure.

The key ISO Standards relevant within the Energy aspects

- ISO 50001:2018 (Energy Management): This is the most crucial standard, providing a framework for mining companies to implement energy-efficient technologies, reduce consumption, and lower operational costs, aligning with decarbonization goals.
- ISO 14001:2015 (Environmental Management Systems): Helps mining operations identify and mitigate environmental impacts, including reducing energy-related carbon emissions.
- ISO 14040 & ISO 14044 (Life Cycle Assessment - LCA): These standards guide the evaluation of energy consumption and environmental impact across the entire mining life cycle, from exploration to closure.
- ISO 50004:2020 (Guidance for implementing ISO 50001): Provides practical guidance for establishing and improving energy management systems in industrial settings like mines.
- ISO 14064:2018 (Greenhouse Gas Accounting).
- ISO 9001:2015 (Quality Management Systems): While general, it streamlines operational efficiency, which indirectly optimizes energy consumption in processing plants.

DINAMINE