illuMINEation

THE FUTURE OF MINING

REQUIREMENTS OF THE MINING INDUSTRY

This Deliverable D2.1 presents the particular requirements of the illuMINEation Use Case partners in connection with sensors, data transfer modes, storage systems, data analysis and visualisation.

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Abstract:	This document lists the needs of the mining industry in terms of increasing innovation related to the use of modern sensors and analytical algorithms.

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Executive Summary

In this document, mining partners of the *illuMINEation* consortium have defined their innovation needs in order to improve mine safety, optimise their operations and therefore increase the efficiency of the mining process, ore processing and reduce operating costs. Proposed solutions are applicable not only to the *illuMINEation* Use Case partners but to the entire mining industry.

The first proposed solution is the development of “intelligent” rock bolts that would allow to monitor rock mass conditions and stabilities in the vicinity of mine workings in addition to providing information on rock bolt’s operational status, durability and proper functioning. This will allow to continuously monitor whether a particular rock bolt is damaged and hence should be replaced by a new one. Moreover, the intelligent rock bolts should feature even more functionalities. Thanks to a set of sensors mounted on their heads, the bolts will be capable to monitor atmospheric conditions in the mine workings, in order to determine whether there are excessive concentrations of harmful gases, smoke that could be a sign of fire, or that the ventilation is working properly.

Another solution proposed by the Use Case partners is the process of measurement and analysis of rock mass during the drilling of holes in mine workings – the so-called Measurement-While-Drilling (MWD) and Analyse-While-Drilling (AWD) methods. Information acquired by these methods would improve decision-making process with respect to exploitation (e.g. resource grade control), geotechnical aspects (e.g. blast design and selection of ground support standards) or selecting the appropriate ore blending for optimised mineral processing. The MWD/AWD technologies would allow for an immediate updating of the geological and resource model of the deposit, considered as highly important for production planning. All of these aspects affect the efficiency of mining operations influence operating cost and its potential optimisation and reduction.

Currently, mining is commonly conducted with mining machines. The environment in which mining machines operate is extremely demanding and their parts wear out quickly, with the effect of breakdowns and downtime. Working conditions and reliability of this machinery is key to raising or maintaining efficiency at a good level. Mining partners suggested that it would be beneficial to be able to monitor the condition of the machines, but also to predict possible failures. Thanks to such information the maintenance staff could prepare spare parts in advance and keep the machinery in good technical and operational condition.

Other solutions have also been proposed on mining machinery, such as the operational implementation of battery-powered electric machines or autonomous machines.

In addition to the exploitation of the ore deposit, there are many additional processes in mining. This report also includes solutions concerning surface infrastructure, e.g. tailing storage facilities (TSF) that are intended for post-mining waste storage. In this case, it is important to monitor the state of embankments of such facilities in order to be able to quickly respond to possible threats related to seepage or dam failures. Most of such TSF objects are already closely monitored. However, the amount of collected data is so large that it is difficult to process. Hence, algorithms for data analysis using machine learning or artificial intelligence are being proposed.

The last solution presented in this Deliverable is related to the monitoring of mining impact on the natural environment, being a crucial factor to be taken into account in the modern mining industry. Project partners identified the need to create a device which will be able to monitor several necessary parameters simultaneously, e.g. ground water monitoring in order to determine water quality and to ensure quick response in case of acid mine drainage. Such devices should be relatively low-cost in order to allow for their deployment on a mass scale and to have a broad overview of the mine's impact on its surroundings.

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Industry partners have also identified their needs related to data collection, data transmission and data visualisation from the aforementioned solutions, in order to fully utilise them as expected.

All solutions proposed in this report should be as affordable and easy to deploy as possible so that mining companies are willing to use them and install them in large numbers, especially in the case of the intelligent rock bolts and devices intended for environmental monitoring. This is the crucial factor that will let those solutions fully serve their purpose. Devices also need to be modular in design so that they can be easily used for different types of mines, mineralisation or structural conditions.

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1 Introduction

1.1 Purpose of this Document

The main purpose of this document is to present the needs of the mining industry to improve safety, increase work efficiency and generally raise the level of technological development in this branch of industry.
The requirements presented here have been indicated by the partners of the *illuMINEation* project, however, they can be easily transferred to the entire mining industry.

1.2 Scope of this document

This deliverable covers the requirements of the mining industry along with the proposed measurements, data transmission method, data storage, processing and visualization.
This document does not present any specific technical solutions or requirements for the use of sensors, only suggestions for solutions are presented.

1.3 Related Documents

This deliverable provides a basis for further work in the *illuMINEation* project and the resulting deliverables.

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2 Main Part

2.1 Use Case partners description

2.1.1 Boliden – Garpenberg and Kristineberg mines

Boliden is a base metals company organised into the business areas Smelters and Mines. Its core competences are within the fields of exploration, mining, mineral processing and smelting, but increasingly also sustainability and metal recycling. The company has approximately 5.800 employees. Boliden owns and operates 6 mining operations in Finland, Sweden and Ireland, mainly producing Cu, Zn, Pb, Ni, Au and Te concentrates.

Boliden participates in *illuMINEation* as a Mining Industry Use Case partner, with primary focus on intelligent rock bolts for geotechnically safe zones in the underground mines. The company installs approximately 400.000 rock bolts per year in order to create a safe underground work environment. "Sensorised" intelligent rock bolts will continuously monitor and transfer information on the bolt's operational status via underground communication networks, already available in the Boliden mines. Such monitoring system would allow mines to identify areas where rock support requires rehabilitation or underground areas that need to be evacuated or even abandoned. The intelligent rock bolts will be tested in two Boliden mines with different rock conditions: Kristineberg, with relatively soft rock and large deformations, and Garpenberg with more brittle rock and seismic activity.

Kristineberg mine is located 90 km west of Boliden town, approximately 750 km north of Stockholm, Sweden. Complex sulphide ore containing copper, lead, zinc, gold and silver is mined from 850 to 1350 meters depth. Main mining method is overhand cut and fill / drift and fill. Annual ore production amount to 605kt.

Kristineberg mine is a volcanogenic massive sulphide ore deposit. Ore deposit consist of many smaller ore bodies. Figure 1 below shows different ore bodies, top view. The host rock for mineralization is Chlorite-Schist, in some parts also Sericite-Schist and Talc-Schist. Further away, the mineralization is surrounded by Chlorite-Quartzite and Sericite-Quartzite.

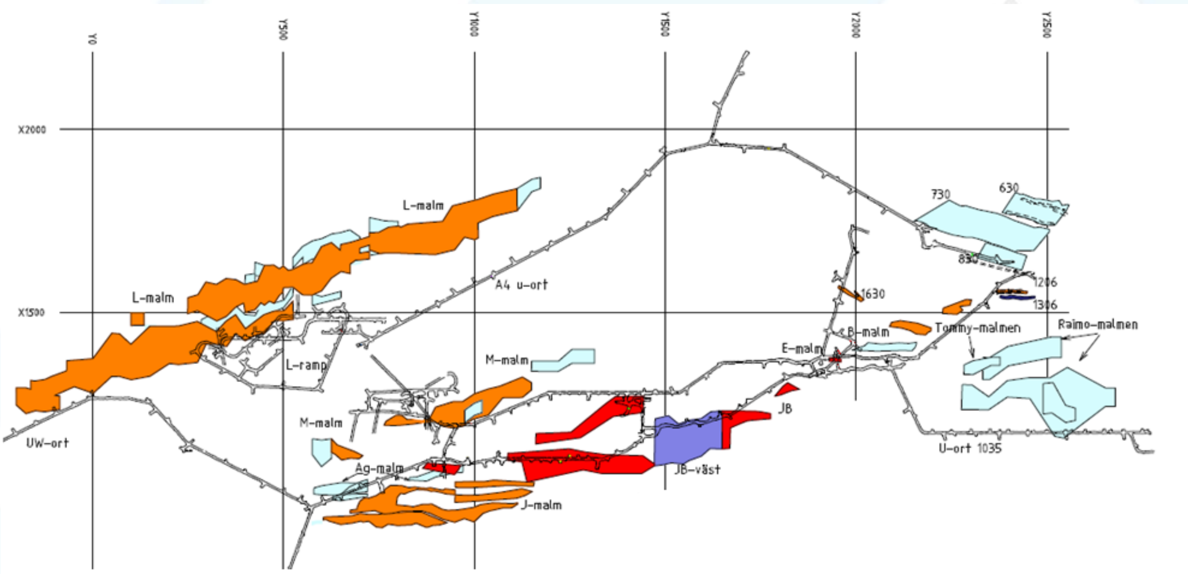

Figure 1: Map of Kristineberg mine.

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Kristineberg is, despite being a hard rock mine, relatively soft. Uniaxial compressive strength of the host rock is in the range of 100 +/- 50 MPa, but it often drops to 25-50 MPa. Additionally, the strength of the rock mass occasionally changes several times along the same mined cut. High stresses in combination with soft rock causes large deformations in some areas. Mining induced seismicity is very rare because of the soft rock and is not considered to be a stability issue.

The rock support operation cycle in Kristineberg mine consists of mechanical scaling, shotcreting and systematic bolting. Steel fibre-reinforced shotcrete at 50mm thickness is applied to the rock surface and a square bolting pattern installed. Main bolt patterns are 1 x 1m, 1.2 x 1.2m or 1.5 x 1.5m depending on the rock conditions.

The rock bolts are 20mm diameter, 2.7m long fully resin or cement grouted rebars. A face plate 100x100x10mm is attached to the bolt with a nut. Bolt installation is performed with bolting machines from Epiroc.

Figure 2: View of the drift in Kristineberg mine.

If rock conditions are particularly poor, complimentary reinforcement are applied. There are two standard complimentary methods used in the mine:

1) 5m long 20mm diameter rebar bolts, 2 x 2m (without plate) in roof or spot bolting in the walls
2) bolt arches with 2.7m bolts, c/c 0.6m

Garpenberg mine is located 180km northwest of Stockholm, Sweden. Garpenberg is a polymetallic underground mine operating from 450 to 1400 meters depth mainly using long hole open stoping with paste backfill. Ore production reached 3 Mt in 2020.

Garpenberg mine is a volcanogenic hydrothermal deposit. Metals dissolved from an active large and shallow marine rhyolite-dacite volcano, rise up to an extensive limestone reef at the sea floor which acted as a barrier and chemically trapped and concentrated the metals to form the polymetallic sulphide deposit.

Garpenberg mine is a hard rock mine. Mining-induced seismicity is common and occurring at local magnitudes up to M_L=2.3. Rock bursts (fall of ground caused by a seismic event),

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however, is rare. In high stress areas dynamic rock support is used to prevent this from happening. Mining is also done in high stress areas with relatively soft ground which causes large deformations. Deformations can exceed 0.3m in the back. Ground support rehabilitation (installation of new reinforcement) is necessary in these areas to ensure stable conditions.

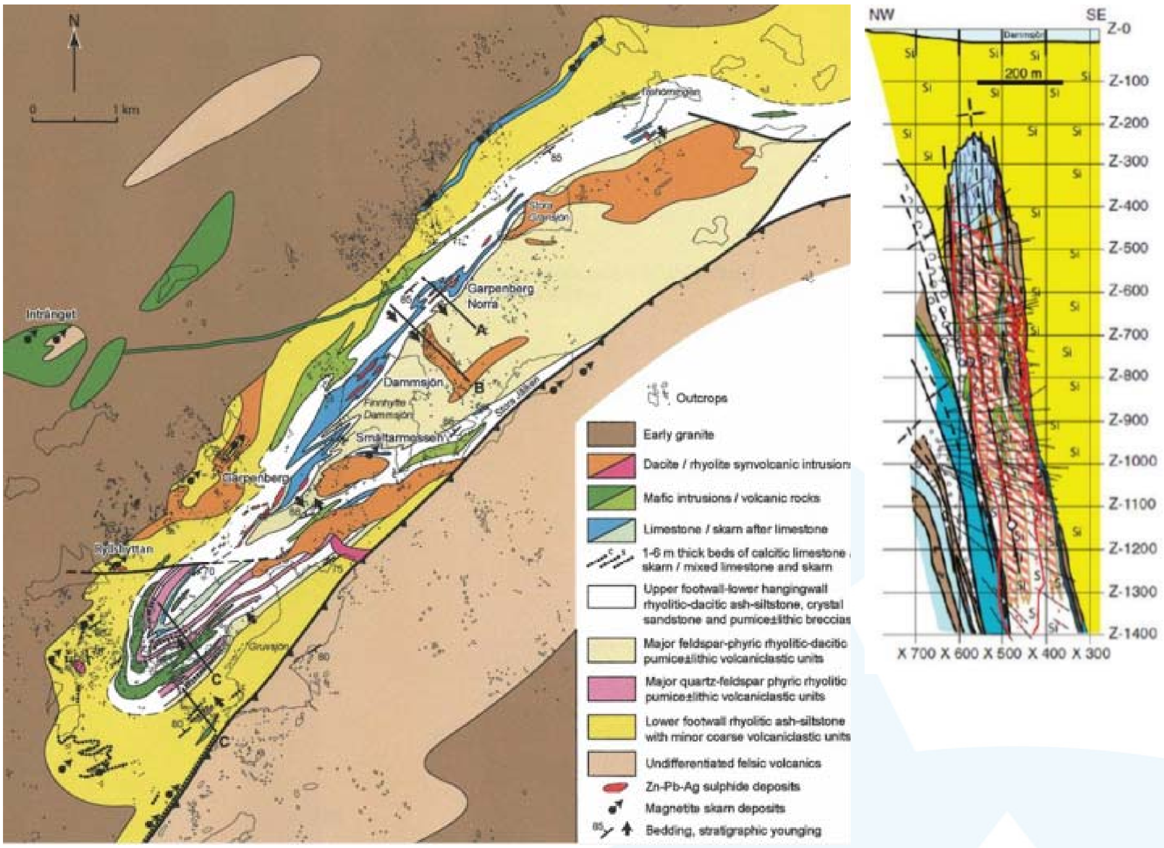

Figure 3: Geological map of Grapenberg mine area.

Referring the deployed rock support standards, after mechanical scaling, a steel fibre-reinforced shotcrete at a standard thickness of 50mm is applied to the rock and then systematically bolted. A square bolting pattern with 1 to 1.5m distance between bolts is applied. Standard bolts are 25mm diameter, 2.7m long fully resin grouted rebars. A systematic bolting pattern drawing from Kristineberg and a photo from a 10m wide and 5m high drift in Garpenberg is shown in the Figure 4. Bolt installation is undertaken with bolting machines from Sandvik.

Dynamic rock support consists of steel mesh and fully resin grouted 25mm diameter, 2.7m long D-bolts with three anchors.

The communication systems in Boliden underground mines are currently based on wireless network technology. The Wi-Fi 5 standard is used for IP phones, Wi-Fi positioning and radio. In total there are more than 4000 access points installed throughout Boliden's underground mines where distance between access points is less than 150m. The mines are moving towards Wi-Fi 6 in the near future in order to reduce power consumption. Tests with 4G (LTE), 4G+, and 5G together with Ericsson had been done in the Kankberg mine.

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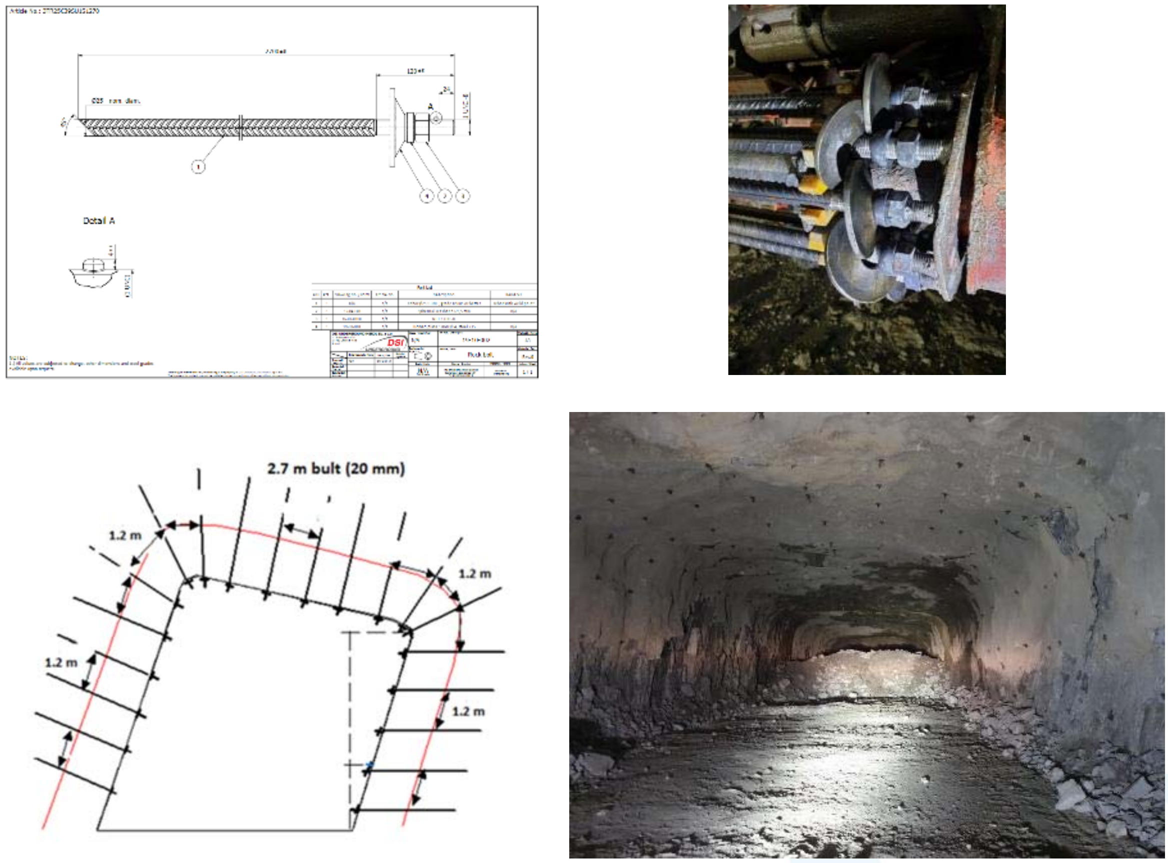

Figure 4: Rock bolts installed in Grapenberg mine and view of a drift.

The following "IIot"-connections are implemented in the mines:

- ABB 800XA - control system for hoist, pumps, fans, ventilation doors, crusher, conveyors, mill, water treatment etc.;
- Mobilaris (https://mobilaris.se/mining-civil-engineering/mining/) - used for situational awareness (Wi-Fi tags in vehicles and on personnel, visualized on mine map), underground path finding guidance, alerts on oncoming traffic and emergency support (rescue chambers, location of personnel and rescue team);
- Ventilation on Demand (VOD) - tags in equipment controls auxiliary fans who in turn controls main fans (different types of underground machines call for different air volumes);
- Remote blasting - control fans and ventilation doors in addition to on-line gas sensors for monitoring of blast fumes at certain locations;
- Intelligent sump pumps (IDD);
- Mobile mining equipment (Epiroc Certiq, Sandvik Optimine) – remote control and automation, also tracking performance and condition data;
- Mine Operation Central (MOC) for work orders and reports, moving from radio and paper towards digital communication. Tablets will be used for all operators or in machines to enable access to Boliden Intranet, maps, plans, checklists etc.;
- Drill rig navigation systems for geo reference;
- Various types of apps to support mining operations, geologists etc.

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2.1.2 Epiroc – mining equipment

Epiroc is a leading global productivity partner for the mining, infrastructure and natural resources industries. With ground-breaking technology, Epiroc develops and produces innovative, safe and sustainable drill rigs, rock excavation and construction equipment and tools. The equipment is generally used in industries for surface and underground mining (incl. drilling and rock excavation), infrastructure development, well drilling and geotechnical applications. The company also provides service and solutions for automation and interoperability. Epiroc is based in Stockholm, Sweden, had revenues of BSEK 41 in 2019 and has about 14,000 employees supporting and collaborating with customers in more than 150 countries. Until mid-2018 Epiroc was part of the Atlas Copco Group founded in 1873, subsequently forming a separate independent company.

Epiroc's Underground division develops, manufactures and markets a wide range of tunnelling and mining equipment, including drill rigs, loaders, mine trucks and ventilation systems, for underground applications worldwide.

In their product portfolio there are:

- 14 models of face drill rigs
- 7 models of production drill rigs
- 4 models of electric underground loaders
- 9 models of diesel-powered underground loaders
- 1 model of electric underground dump truck
- 9 models of diesel-powered underground dump trucks

Figure 5: Some of Epiroc's products: Scooptram loader, Boomer drill rig and Minetruck dumper.

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Figure 6: The Scooptram ST14 loader equipped with a streaming data unit.
The unit will be utilised for collecting data in the *illuMINEation* project.

Epiroc focuses on innovative product design and aftermarket support systems for added customer value. The Underground division has production in Sweden, India and China.

Epiroc is participating as partner in the *illuMINEation* project and contributing with the knowledge about drilling and material handling in underground applications. Epiroc is actively participating in R&D project consortia in order to develop and contribute towards a more intelligent and sustainable mining industry. The scope in IlluMINEation including predictive maintenance, battery surveillance systems, sensor and data analytics, as well as selected tests in Epirocs's test mine facilities aligns well with the other four involved mining company Use Case partner's needs. Epirocs want to contribute to an effective utilization of our machines in the mining production chain, and sees the need to improve a system of sensors installed on mining equipment and to develop new algorithms for predictive maintenance and operational improvement.

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2.1.3 KGHM Polska Miedź – Żelazny Most TSF

KGHM Polska Miedź S.A. is one of the largest producers of silver and copper globally. In Poland, KGHM operates three underground mines, processes ore in two processing plants, has two smelters and the largest tailings storage facility in Europe.

A Tailings Storage Facility (TSF) is a structure made up of one or more dams built to store the uneconomic waste residue consisting of ground-up rock, sand, silt and water during the mineral processing steps. The TSF is considered a high-risk structure that can cause in the event of structural damage or failure big damage to the natural environment, also having the potential to cause loss of human lives. However, it plays a crucial role in the mining operation. Because of the high risk, it must be monitored carefully with highest standard monitoring systems and a qualified monitoring team. The awareness of tailings dam safety monitoring and reviews has increased due to catastrophes resulting from failures of such dams, and even worsened as a consequence of increasing tailings waste capacities and construction of larger dams. In the reported 18,000 tailings dams around the world, the failure rate of such facilities in the past 100 years is estimated at 1.2%, the failure rate of the traditional water storage dams, however, is only 0.01% (ICOLD, 2001). Hence, the failure rate of TSF structures is 100 times higher than other conventional water-retaining dams. The recent increase in TSF failures may be attributed to the combined effect of rapid embankment construction along with poor rapid monitoring (Azam, Li, 2010). Some reasons can be pointed out why the tailings dams are more prone to fail when compared to water storage dams i.e.:

- Embankments built with residual material from mining activities.
- The amount of wastewater increases with the height of dams.
- Continuous necessity of monitoring in order to assure the dam stability.
- Cost of monitoring the tailings dams is high during mine operation and closure.
- Lack of reasonable regulation on design standards.

It is also highly important to examine the mechanism of the dam's failure and adopt all possible means of enhancing their safety. The major causes of Tailings dam failures can result from:

- Seepage and internal erosion.
- Poor foundation conditions.
- Overtopping.
- An earthquake effect causing static and seismic instability.
- Other reasons such as mine subsidence, structural, external erosion.

Possible failure modes in tailings dams have to be recognized in any dam safety study and proper safety monitoring procedures have to be exercised to eliminate possible dangers of any failures and their consequences. Key failure modes have been identified by U.S Committee on Large Dams (USCOLD) and the number of failures attributed to each mode is summarized from 106 incidents (Bligh and Fourie) in Figure 7.

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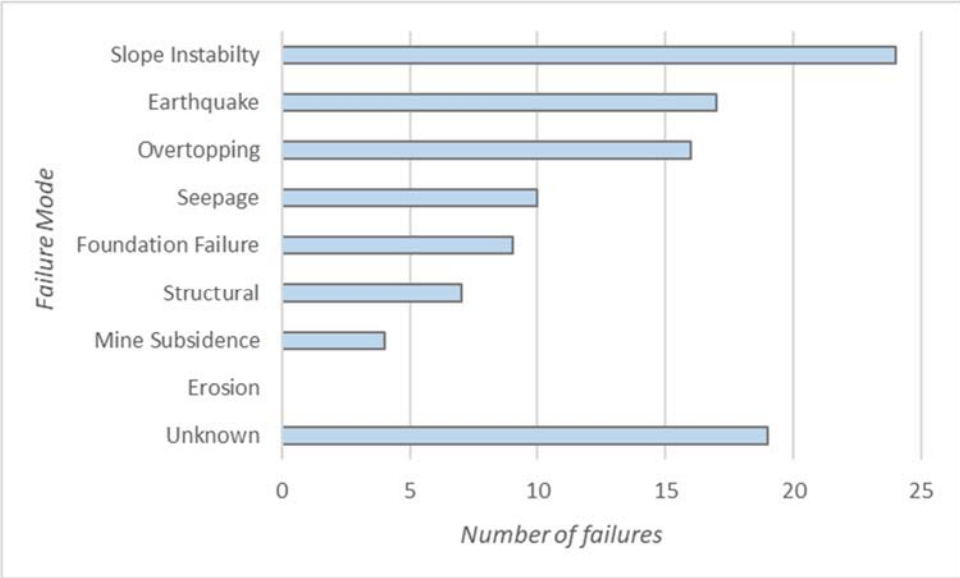

Figure 7: Failure modes of TSF and frequency distribution (Bligh and Fourie).

Failures caused by earthquake are difficult to mitigate, but all other modes can be monitored and reasonably predicted given that adequate information is available. In summary proper understanding of the failure mechanisms together with sufficient supervision and good management of the operation of TSFs help to eliminate causes of such failures. The monitoring parameters that should be analysed to mitigate the risk of failure are presented in the table below.

Table 1: Failure modes and corresponding monitoring parameters (Adamo et al., 2020).

Failure mode	Monitored parameter
Slope instability	displacement, settlement, pore pressure change, shear zone occurrence, liquefaction potential
Earthquake	ground acceleration, pore pressure change, displacement
Overtopping	water surface of the pond change, pore pressure change
Seepage	seepage quantity and quality
Foundation	displacement, shear zone occurrence
Structural	displacement, cracks
Mine subsidence	ground acceleration, settlement
Erosion	Effluent quantity and quality change, surface elevation changes

In the *illuMINEation* project, the Tailing Storage Facility "Żelazny Most" managed by KGHM Polska Miedź company will serve as an experimental structure to develop Machine Learning algorithms to improve the analyse of the monitoring data from TSF structure. Żelazny Most TSF is one of the world's largest copper tailings disposal facilities, located at Żelazny Most in south-west Poland.

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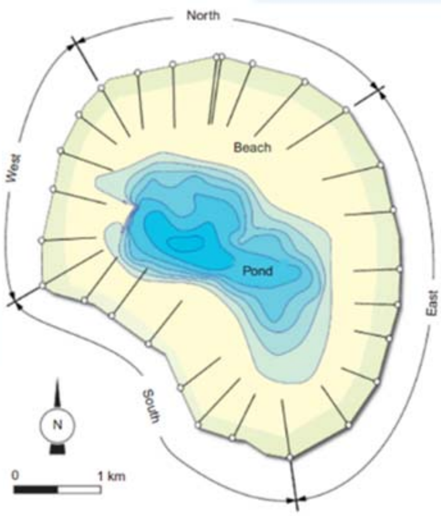
Figure 8: Location of Zelazny Most TSF.

Its operation commenced in 1977 and, by the end of 2020, 660 million cubic meters of tailings had already been stored within a confining embankment dam ('ring dam') of about 11.8km in total length. The foundations of the ring dam lie on Pleistocene deposits, underlain by a thick sequence of Pliocene sediments. As with all tailing dams, the Żelazny Most disposal poses many challenges for the geotechnical engineer, in particular flow liquefaction of the stored tailings, which potentially threatens the stability of the confining dams. This in turn depends on the height of the dam and the mechanical behaviour of the foundation soils. The Żelazny Most dam, which surrounds the tailings disposal, will hereafter be referred to as the 'ring dam'. The original ground surface where the disposal facility is placed was saddle-shaped, so that the eastern and western portions of the ring dam are higher than those to the north and south. The present elevation of the crest of the ring dam ranges between 187.5 m and 190.0 m above sea level.



Dam length	11.79 km
Total area	~ 14 km2
Beach area	556 ha
Pond area	550 ha
Water volume	~ 7.70 mln m^3
Tailings volume	~ 660 mln m^3

Figure 9: Schematic plan view of Zelazny Most TSF.

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The Żelazny Most tailings dam is being raised using the upstream construction method (see Figure 10). The shell of the dam is built using the coarser tailings, which are fine sand with a low-plasticity (IP < 10%) silt fraction, separated from the remainder of the tailings by spigotting. The construction of the Żelazny Most starter dam was done from local earthen material. Since the beginning of the construction, the dam crest has risen at a rate of approximately 1.0 to 1.5 m/year, constructed with an average downstream slope of 3.5 horizontal to 1 vertical (Jamiołkowski, 2014). Furthermore, the beach (i.e. the distance from the dam crest to the pond edge) is maintained with a length of not less than 200 m. A schematic cross-section of the dam construction is presented below.

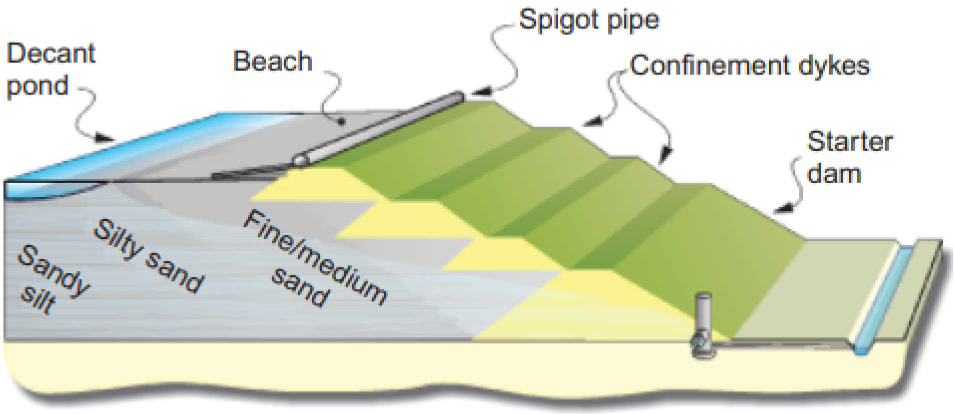

Figure 10: Schematic dam construction cross section.

Another matter that is of interest to KGHM which would definitely improve the efficiency of work, as well as safety in terms of its impact on the environment, is the automated monitoring of groundwater including early warning systems. The monitoring of groundwater and surface waters in the impact area of the mines of KGHM Polska Miedź S.A. began before the commencement of mining operations and has been carried out since the 1960s.

Along with the exploration of subsequent copper-bearing areas and in relation to the progress of the exploitation of copper ore deposits, the monitoring network is continuously expanded by new measuring points with selected observation points being liquidated.

Since 2007, the monitoring system for the dynamics and chemistry of ground and surface waters in the observation areas of three operating mining plants (O/ZG "Lubin", O/ZG "Rudna" and O/ZG "Polkowice - Sieroszowice") had been unified.

The observation network consists of: dug wells, shallow (quaternary) piezometers, deep (sub-Pleistocene) piezometers and control and measurement sections on surface waters.

The observation network consists of:

- 245 dug wells,
- 142 piezometers capturing the Quaternary level,
- 95 piezometers capturing deeper aquifers (IR), and
- 69 measurement points located on surface waters.

Manual measurements of the position of the water table in the observation wells and flow measurements on surface watercourses are performed 4 times a year.

Determination of the physicochemical parameters of waters is based on laboratory tests, which are performed 2-4 times a year.

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In 27 piezometers capturing deeper aquifer levels, measurements are made with digital sensors (measurement of pressure = water column above the sensor and temperature) with the frequency of measurements every 5-15 minutes.

Total depth of observation holes: 1.4m-over 1000m.

Water table depth: 0.5-800m.

Total area under observations: 780 km^2.

The purpose of conducting these measurements is to assess the impact of mining activities, including mining drainage, on the quantitative and qualitative condition of groundwater and surface waters, and the assessment of the abundance of aquifers in order to forecast the size of the inflow of groundwater to mine workings and shafts.

2.1.4 Minera de Orgiva – Lujar mine

Minera de Orgiva S.L. is a fluorspar mining and trading company and falls within the small and medium-sized enterprise (SME) category. Fluorspar is considered a priority commodity by the EU and is included in the list of Critical Raw Materials.

The main activity centre is the “Mina Lújar”, in Orgiva, Granada (South of Spain). It is a small and narrow-vein deposit, characterised by very complex ore distribution due to geological and tectonic factors, making its underground mining highly sensitive to costs.

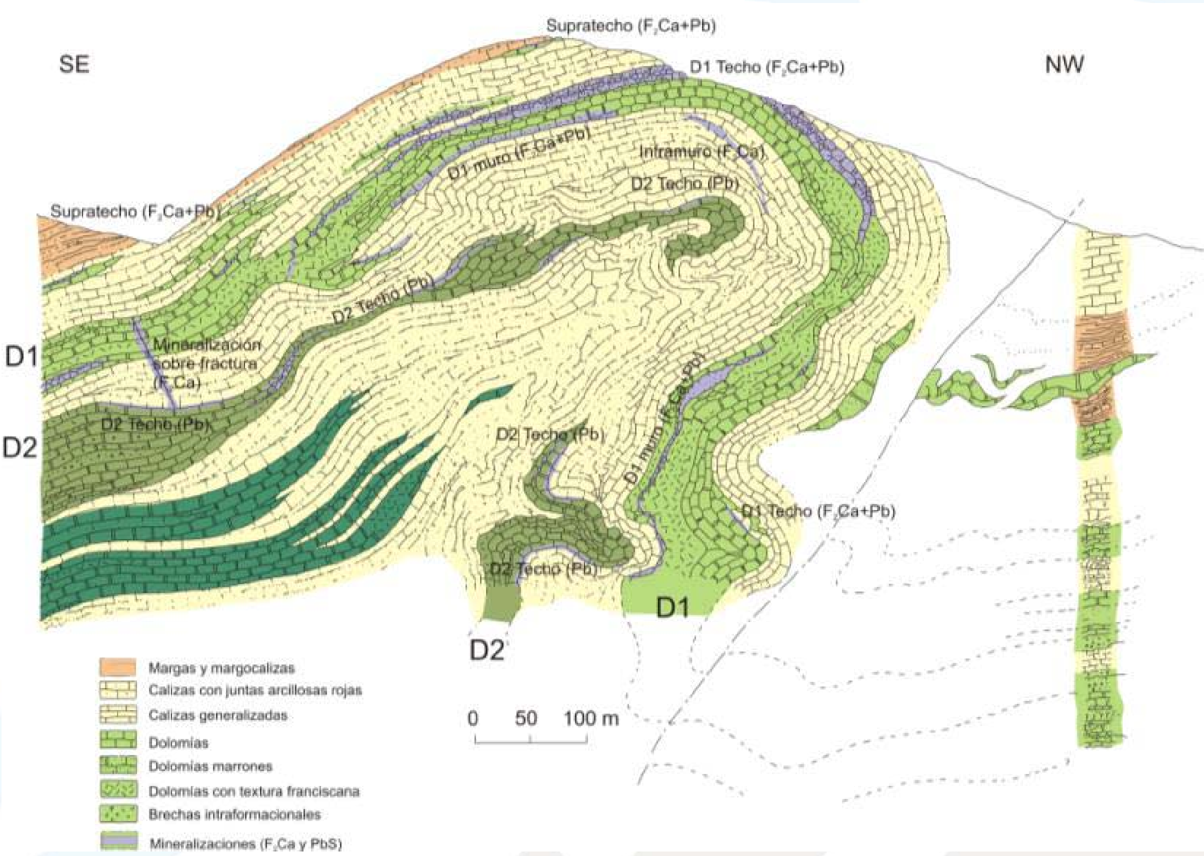

Figure 11: Geological cross section of Lujar mining area (violet colour - fluorspar deposit).

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The Minera de Orgiva mine operation cycle consists of a first stage drilling via an Atlas Copco Jumbo model L2C or Boomer 282 of the area planned and scheduled to be extracted. During drilling, some samples in different locations are collected and analysed by X-Ray fluorescence (XRF), in order to assess ore grade and decide whether this material will to be sent to the processing plant or is considered waste. The second stage is blasting and subsequent scaling. Depending on the quality of the rock, roof and walls support via shotcrete and/or bolts is applied. Subsequently, the stope is surveyed by photogrammetry for accurate estimation of the volume extracted by the blast, closing the cycle.

Due to the geological characteristics of the deposit and the particular shape of the orebody, technology that allows to determine the rock mass mechanical and structural characteristics (MWD), and the chemical composition of the rock already at the drilling stage would be very useful. It would allow for faster decision making in many respects:

- how to proceed with the exploitation and continuation of operation in a particular area of the mine, or whether it is better to move to another place;
- increase the efficiency of explosives use
- improve fleet management and utilisation of mining equipment, directly translating into cost savings.

Portable XRF devices do not perform well with fluorine recognition due to its low atomic weight. Therefore, MDO has a high priority in contributing to developing a new technology for rapid, mobile and accurate estimation of the fluorine content to be used in the drift.

In addition to measurement while drilling and analysing while drilling technology, the company seeks to implement solutions that allows to predict failures of mining equipment. The machinery used MDO's mining operation is already relatively old and failures are becoming more frequent and leading to production delays.

Most drifts in the Lujar mine are relatively stable and the use of shotcrete as ground support to secure the area is generally sufficient. Nevertheless, there are certain locations that require installation of rock bolts for roof support. The use of "sensorised" intelligent rock bolts would allow to monitor the condition of an intensely folded rock mass and counteract possible hazards.

At this moment there is no WiFi network installed in the mine that could be used for data transfer to the data storage and processing platform from above-mentioned solutions. However, Minera de Orgiva has already commenced work on the deployment of a WiFi network in order to integrate the solutions of the *illuMINEation* project.

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2.1.5 RHI Magnesita – Breitenau mine

As leading global supplier of refractory products, systems and solutions with a strong drive for innovation and digitalization, RHI Magnesita participates in several work packages of the *illuMINEation* project. The particular Use Case concerns RHI Magnesita's underground magnesite mine located in central Austria in the eastern alps. Mineral deposits of the alpine type tend to be geologically disturbed, resulting in irregular deposit shape, complex natural jointing systems, excessive faulting and therefore represent a big challenge for mine design concerning stability issues. Stress situations are usually complex and difficult to assess due to the tectonic history of the formation of the alps and the irregular topography. The Breitenau magnesite mine is typical of alpine mineral deposits and highlights the complex geological and mining situation encountered in the alps. The magnesite deposit Breitenau represents the largest known sparry magnesite deposit in the eastern alpine region. The deposit dips with 20-25° to the south and south-east and possesses a thickness between 50 and 200m. In dip direction the deposit extends over a distance of two kilometres and in strike direction over a distance of up to 500m. Characteristic features of this deposit are the bedding between two schist layers and the multi-phase tectonic history resulting in multiple discontinuities and faults. (Figure 12) The mining activities are conducted in an open pit and an underground mine, with a total annual production of 500,000t magnesite. The activities are distributed over five mining sections: in the upper four sections the "Post pillar mining" method is used, whereas at the lowermost section, a system of large rooms separated by slender support pillars is established, whereby the rooms are backfilled with cemented backfill material (Figure 13).

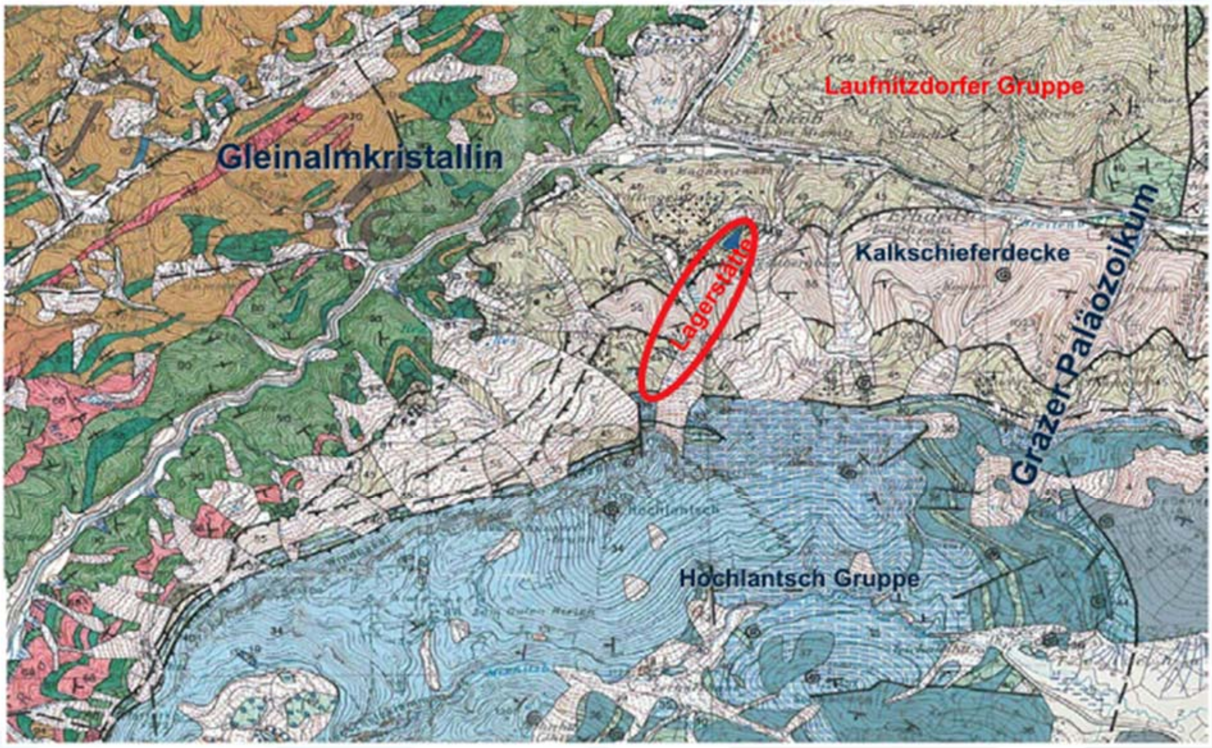

Figure 12: Geologic map of Breitenau mine area.

The depth of cover of the lowest mining section is around 1000m. This significant depth, is one of the biggest challenges encountered in this underground mine concerning transports logistics. The only access to the underground openings is a spiral ramp which is used to transport the material out of the mine by trucks.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 869379.

The mining method (Figure 13) room and pillar mining of the upper mining levels (with backfill) is associated with roof fall risks and pillar stability issues as well as the requirement of large numbers of support measures. Rock bolts are the main ground support instrument in Breitenau underground mine, with about 1 rock bolt per square meter installed in the roof and side walls of the rock mass. In room and pillar mining, the mineral extraction is undertaken in slices in upward direction. This implies that after each slice, all rock bolts are removed and replaced by, resulting in about 14,000 rock bolts being installed every year in the Breitenau underground mine. Rock bolts are installed to maintain the stability of the underground mine.

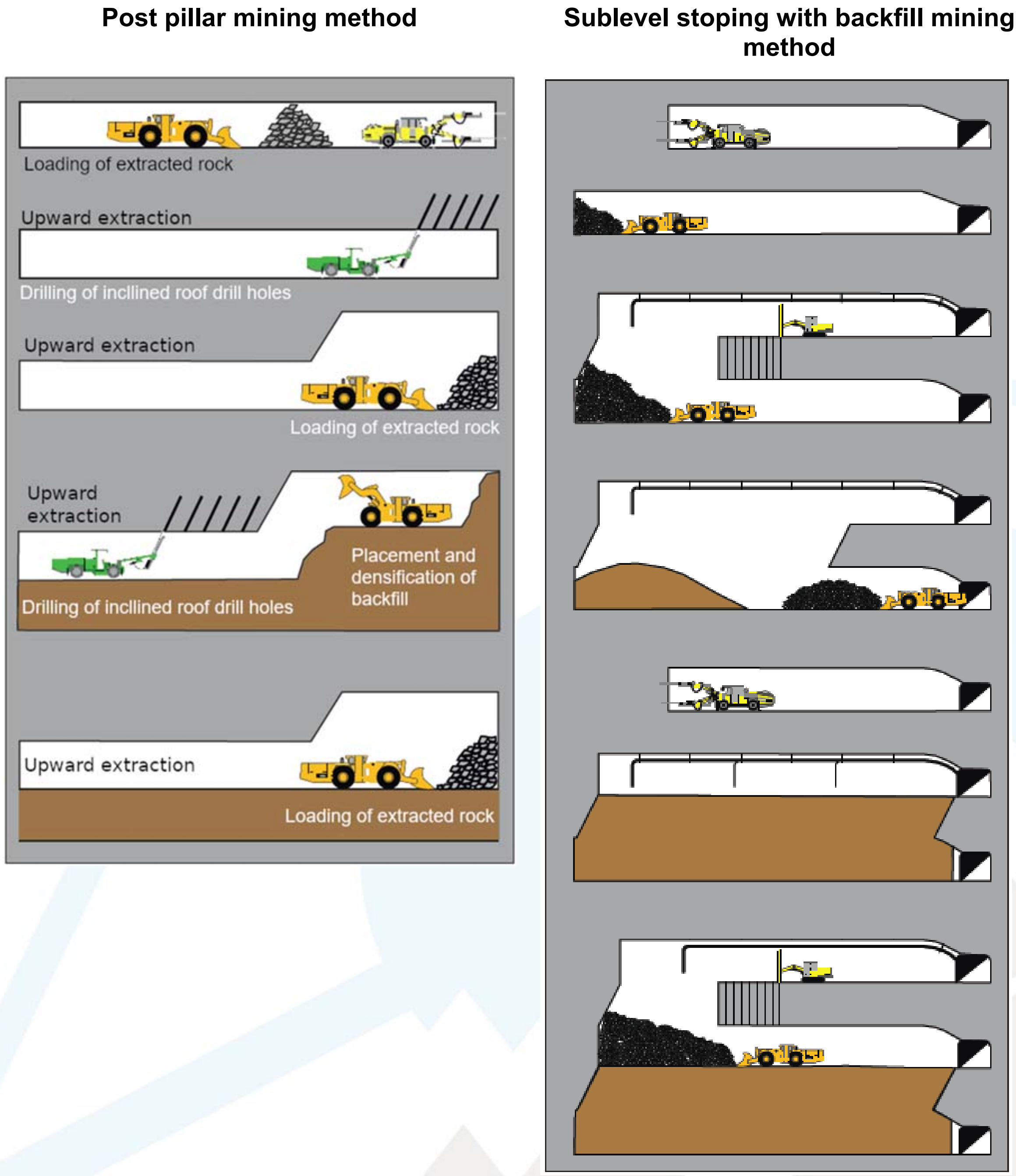

Figure 13: Mining methods in Breitenau mine.

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Within the *illuMINEation* project, RHI Magnesita is further contributing to the development of sustainable and intelligent mineral resource extraction mechanisms, in particular focusing on measurement and analysis during the drilling process. An automated XRF sampling and analysis device is currently in operation at Breitenau mine. It is mounted on a conveyor belt and used to assess the quality of the georeferenced ore stream. The data from this device is used to update the geostatistical model of the deposit and for operational planning. The development of a similar device that would be able to analyse the ore at the drilling stage would significantly help to optimise the costs and operational efficiency of the mine.

Finally, the company is committed to further evolve advanced predictive maintenance and efficient operations, with special emphasis on extending machine data capturing and analysis.

In the upper parts of Breitenau underground mine a WiFi network has been installed that can be fully utilised for data transmission between sensors installed on intelligent rock bolts or on equipment and the IIoT platform for data processing, analysis and visualisation.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 869379.

2.2 Intelligent rock bolts and combo sensor box

2.2.1 Measurement and monitoring needs

Safety of personnel and equipment is considered crucial in modern mining industry. This is particularly important in the case of underground mining, where there are often hundreds of meters of overburden and rock mass overlying underground mining infrastructure. Mining operators must ensure that the deployed ground support standard is appropriate and fulfils its role, allowing all mining personnel to work under safe conditions. Hence, it is crucial to monitor stresses and rock mass instabilities as these are main factors having significant impact on fast prediction of hazards such as rock bursts or rock falls in mine corridors/drifts.

Mining partners participating in the *illuMINEation* project use rock bolts in order to support and secure roofs and walls of mine drifts and stopes. Rock bolts are installed up to a depth of several metres into the rock mass in order to fasten loose and potentially unstable blocks to the stable rock behind. If the rock bolts were able to collect the technical parameters of the surrounding rocks, such as e.g. stresses or displacements, they could become excellent tools providing operators with information about the rock mass in the most vulnerable and hazardous areas. Moreover, sensor-equipped rock bolts will allow to continuously monitor and transfer information on the bolt's operational status. In this perspective such monitoring system would allow mines to identify areas where rock support requires rehabilitation or underground areas that need to be evacuated or even abandoned

Rock stability monitoring via deployment of intelligent rock bolts should be as continuous possible. Rock bursts, roof collapses or outbursts often occur without any prior warning or indication. Data acquisition rates longer than 1 hour may not be sufficient in order to indicate an approaching rock fall event. Frequent data sampling is deemed crucial in gaining a complete picture of the state of the rock mass and geotechnical processes taking place within it. The frequency should not be too high either in order to avoid data overload.

The parameters to be monitored are:

- Axial stresses (extension, compression),
- shear stresses,
- displacements,
- bending moment.

Since the sensors installed on the intelligent rock bolts require a power supply to take measurements and an electronic system for control and data transmission, it seems prudent to also use them in combination with other sensors for monitoring additional parameters on site.

In mine drifts where rock bolts are installed and the ore deposit is being exploited, it is essential to maintain high air quality which is crucial for safe work conditions. Important air quality parameters are gases concentration, temperature and humidity, airflow velocity and direction. Potentially hazardous gases include exhaust fumes produced by mining machines or accumulations of harmful natural gases such as methane or hydrogen sulfide. This data is also important for the monitoring and control of properly operating ventilation systems.

According to measurements currently carried out by mining companies, it is recommended to monitor parameters such as:

CO	O_2	SO_2	Temperature
CO_2	NO	H_2S	Humidity
CH_4	NO_2	Dust	Airflow velocity and direction

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Ideally, sensors monitoring the aforementioned parameters require little or no calibration prior to rock bolt installation. Assuming that the sensors should be installed in large quantities simultaneously with the rock bolts it would be an enormous challenge, or even unfeasible, to calibrate them at specified time intervals, both in terms of time and manpower. Another issue could be related to sensor maintenance due to the harsh and demanding mine environment that commonly is rather dusty and, in case of sulphide deposits, may be highly corrosive. Therefore, sensor casings should be highly resistant and meeting mining equipment standards.

There are various types of geophysical sensors that may be beneficial for safety aspects and possible reconnaissance of the ore deposit. Such sensors would allow to record seismic waves propagation, monitor sounds related to cracking, or displacements within the rock mass, and to detect any shocks and vibrations.

Depending on the real local geotechnical rock conditions, sensors already applied to instrumented or “sensorised” rock bolts could be supported by additional instruments. The following devices are considered to monitor rock mass condition and stability:

- Inclinometers,
- convergence indicator,
- hollow inclusion cell,
- laser scanners.

The last possible sensor could be a module monitoring the quality of the rock bolt installation in the rock mass by determining whether it has been set correctly, the resin used to install has properly bonded and most important, whether the bolt is working properly.

Data provided by these sensors and real time analysis systems will be able to trigger alert prior to a dangerous event occurring.

It is required to know the exact spatial localisation of the rock bolts, hence, the spatial coordinates and the installation angle must be recorded. This is necessary in order to assign parameters registered by the rock bolt to appropriate localisations throughout the mining infrastructure. Without such data it would not be possible to determine if e.g. a rock mass weakening occurs in the roof or in the side wall of a particular drift or stope and, most importantly, where this weakening actually takes place.

The way these sensors are going to be powered is also very important. The simplest solution seems to be the use of batteries installed separately in each rock bolt. However, assuming there are places in mines where rock bolts are installed and are influenced by exploitation of the deposit, both electronic elements and batteries could end up in the mined ore and excavated material. Furthermore, in a situation where areas with installed rock bolts are not exploited, the mining drifts will be decommissioned over time and the batteries in the rock bolts will remain in the rock mass as hazardous waste. Therefore, it should be considered whether it would not be better to use a central power supply for some part of the mine and dismantle it before exploitation or decommission. For now, the power source should be sufficient for about one year of continuous work of sensors installed in intelligent rock bolts.

Taking into consideration that rock bolts are installed in large quantities in mines and given the fact that data collection at high resolution from a large number of acquisition points would be far more useful in terms of dangerous zones identification, it is deemed essential that the proposed solution is available at relatively low-cost and easy to deploy. These are crucial factors in order to ensure the technology is adopted on a wide scale, with the effect of significantly improving mine safety levels.

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2.2.2 Data transfer, storage and analysis

As main data transmission system, mining companies generally prefer to use WiFi networks, as most partners already have the technical infrastructure in place for this type of solution. Currently, it the WiFi5 standard is utilised, which still has some disadvantages in respect to energy efficiency. Hence, the use of LoRa (Long Range Radio) type networks is considered in order to transmit data from intelligent rock bolts to collective hubs that subsequently relay the data via WiFi or cable network to the database servers. The aim of the use of hubs and LoRa networks is to extend the sensors lifetime without the need to replacement the batteries mounted on the rock bolts. The target battery life of the intelligent rock bolts and their sensors is estimated at around at least one year.

According to the initial assumptions within the *illuMINEation* project, an industrial IoT platform with edge/fog/cloud storage facilities will be part of the overall data collection systems, implemented on servers offering high computing capabilities. However, during the realisation of work package two, it became apparent that the best solution might be to combine local IIoT platforms with the *illuMINEation* IIoT platform solution, since most mining companies are often located in areas with limited Internet coverage. In addition, most mining companies with know-how in the area of cybersecurity prefer to store data related to ongoing operations on their own computing infrastructure in order to minimise the potential for unauthorised data leakage. Nevertheless, it is reasonable to assume that not every mining company is that restrictive when it comes to data storage safety. Hence, there will certainly be demand for larger storage services. Highly important cybersecurity aspects are therefore thoroughly addressed in WP7 especially ensuring that current security standards are met in order to protect stored data from a potential data theft or cyber-attacks.

Currently, the amount of data that will be collected and stored on the platform per day in the course of *illuMINEation* is difficult to determine. This is due to the fact that the full range of information on the number of sensors that can be installed on intelligent rock bolts is yet to be determined. Moreover, the amount of data also depends on whether or not it will be possible to determine in which section a potential stress anomaly is located. The spatial coordinates of the mounting point of the rock bolt (X, Y, Z), the installation angle and the length of the rock bolt will certainly need to be stored. It is assumed that each of the proposed parameters in section 2.2.1 will provide one additional data variable, hence, a single rock bolt dataset would consist of about 15 variables in total.

The data collected by a single intelligent rock bolt may not be useful in deeper interpretation of the condition of rock mass, but can only help determine that an anchor is failing if the readings exceed a certain threshold. Only the combination of data from several sensors or the set of rock bolts from specific areas may allow the conclusion that something is happening in the rock mass (e.g. shearing, stress redistributions, compression or bending phenomena occur). That is why it is so important to use algorithms that allow not only to detect anomalies in readings, but also to be able to use data from several sensors at once, correlate them, interpret them and to some extent, draw conclusions about what is changing geotechnical rock conditions.

The algorithms necessary to be implemented as part of the analysis of data from the intelligent rock bolts will be specified in the next stages of the project, as it will be known, what type of sensors can be used and what data can be obtained from them.

2.2.3 Data visualisation

The intelligent rock bolts will be installed in both the roof and walls of drifts, and they are expected to be applied in different mining systems, often in drifts occurring one above the other. Thus, it seems reasonable to use data visualisation in three-dimensional form, with examples shown in Figures 14, 15, 16, 17, and 18 below.

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Figure 14: Overall view incl. filter window for better display and navigation.
(green colour – no warnings, orange – warning, red critical)

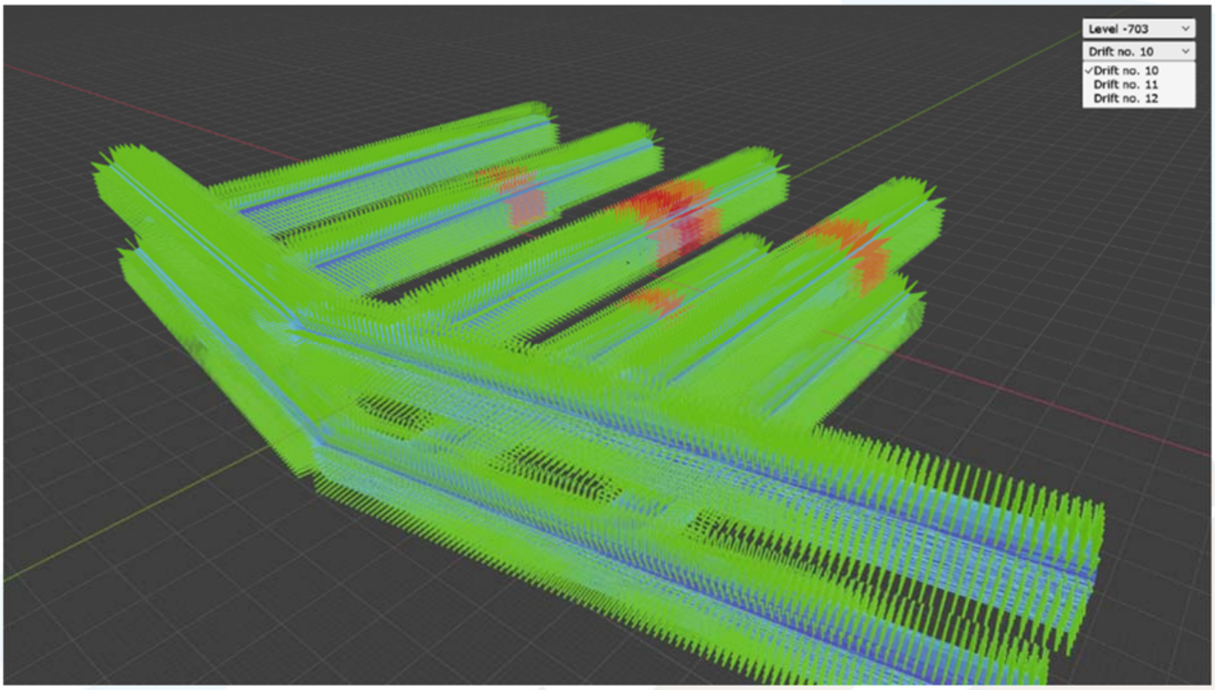

Figure 15: Zoomed In view – particular level or drift.

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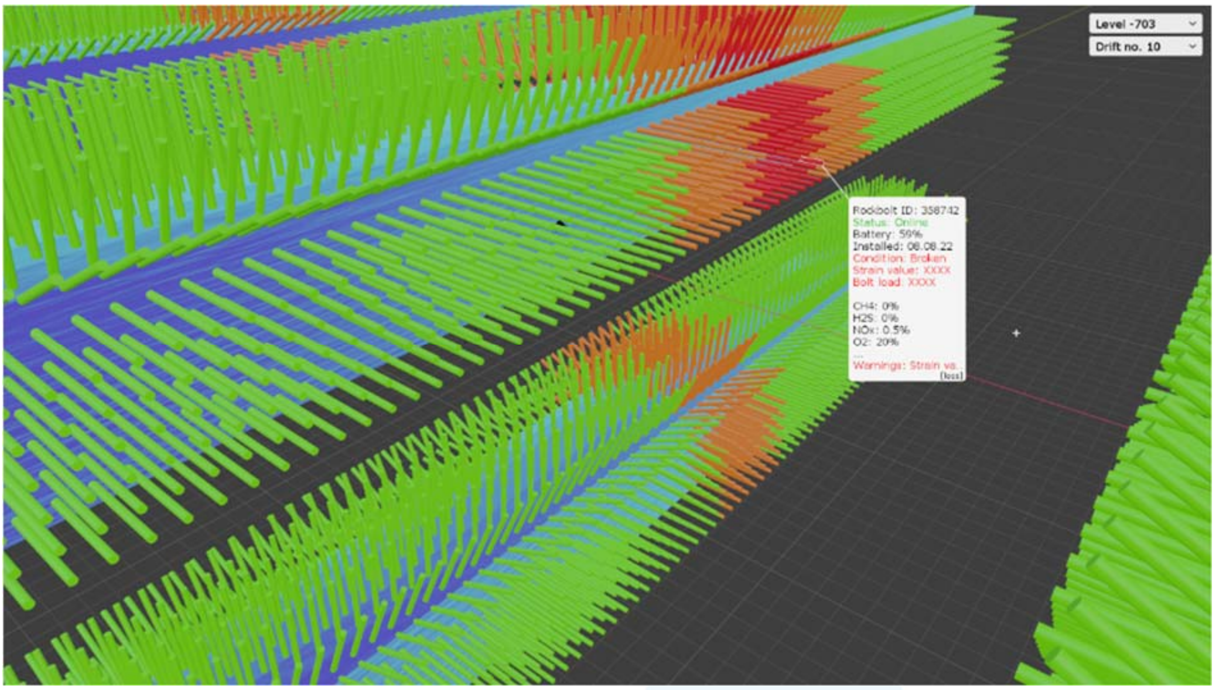

Figure 16: Parameter shown after selecting a rock bolt.

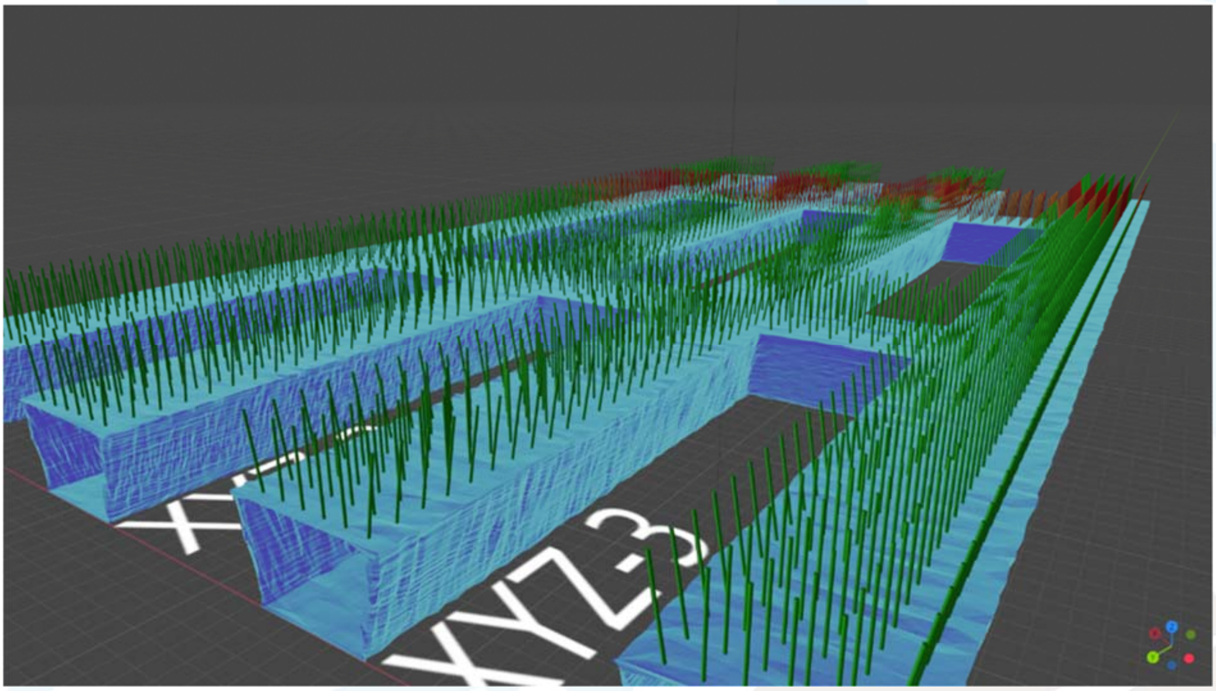

Figure 17: Visualisation for different mining method.

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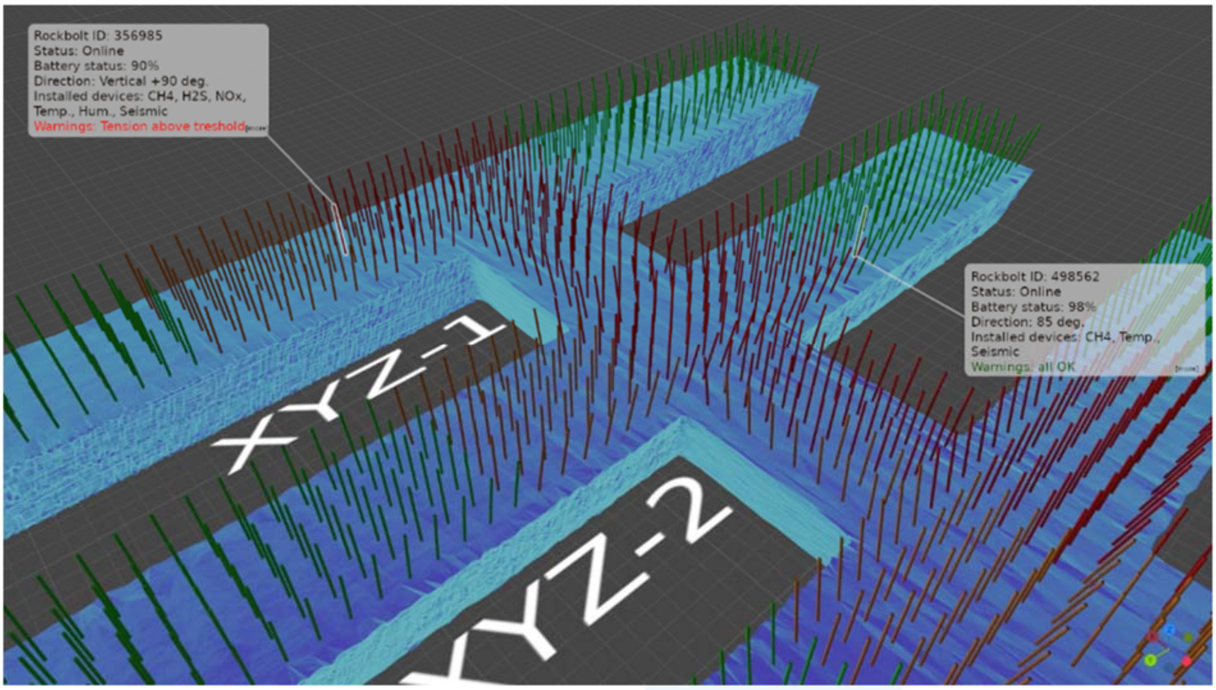

Figure 18: Measured parameters for selected rock bolts.

Rock bolts installed in the drifts are shown and their status may be represented by respective colours. Green colour means e.g. that the condition of a rock bolt is fine, yellow colour means warning condition and red colour means imminent danger. The list of rock bolt data should include date of installation, condition of bolt (failed, not failed), strain along the bolt and bolt load (calculated from strain values). With respect to the alarm triggering process, information on the rock deformation over time (deformation rate, mm/day) is considered highly important, and must also be monitored and identified on the rock bolt visualisations. In case of rock bolt failure, there should be an option to generate a report if possible, showing where the bolt is broken similar to extensometer with several anchors. Filtering of data is also considered important for visualisation, for instance to study critical strain values on bolts for larger mining areas. Another useful filtering option would be to filter out ”old” rock bolts that have been replaced by new ones.

As three-dimensional data visualisation requires powerful computing hardware, it would be advantageous to implement an option to use a 2D view only (Figure 19), with the option of switching between pre-set levels, drifts and roof/walls views.

To simplify visualisation when viewing larger areas of the mine is required, it is proposed to use heatmaps generated from statuses of rock bolts instead of viewing detailed technical data. Additional point information about status data in a particular area could appear as a tooltip when the cursor hovers over a particular colour patch (Figure 20).

Data visualisation should be available on both mobile devices and desktop computers, as the primary users are going to be foremen, surveyors, geotechnicians, geologists and mine managers.

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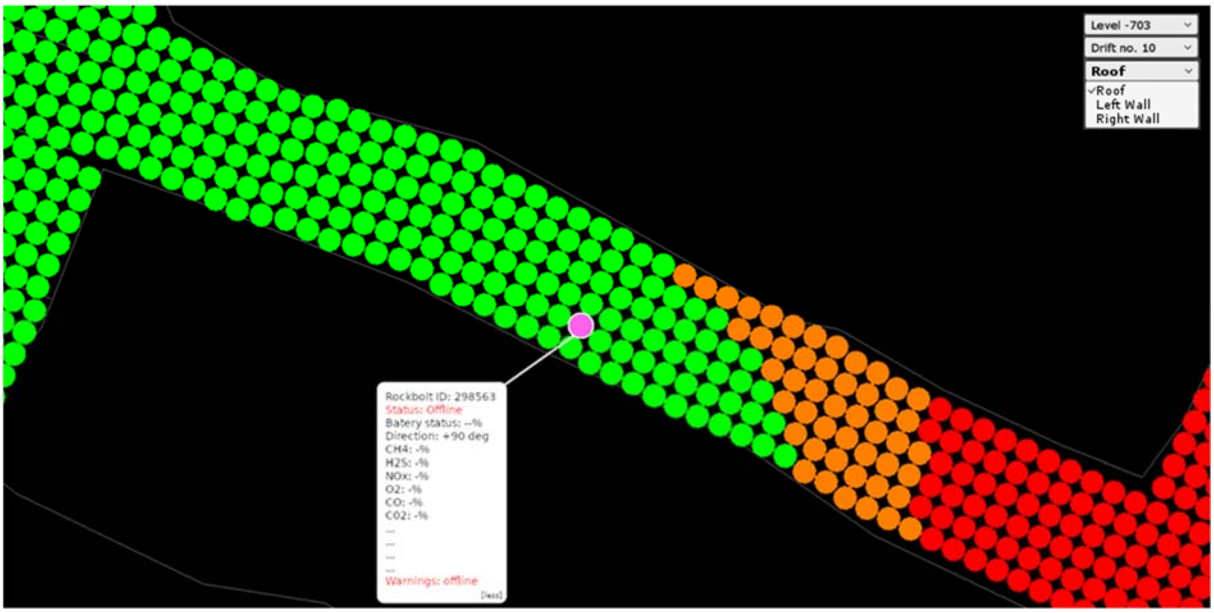

Figure 19: 2D view with rock bolt parameters.

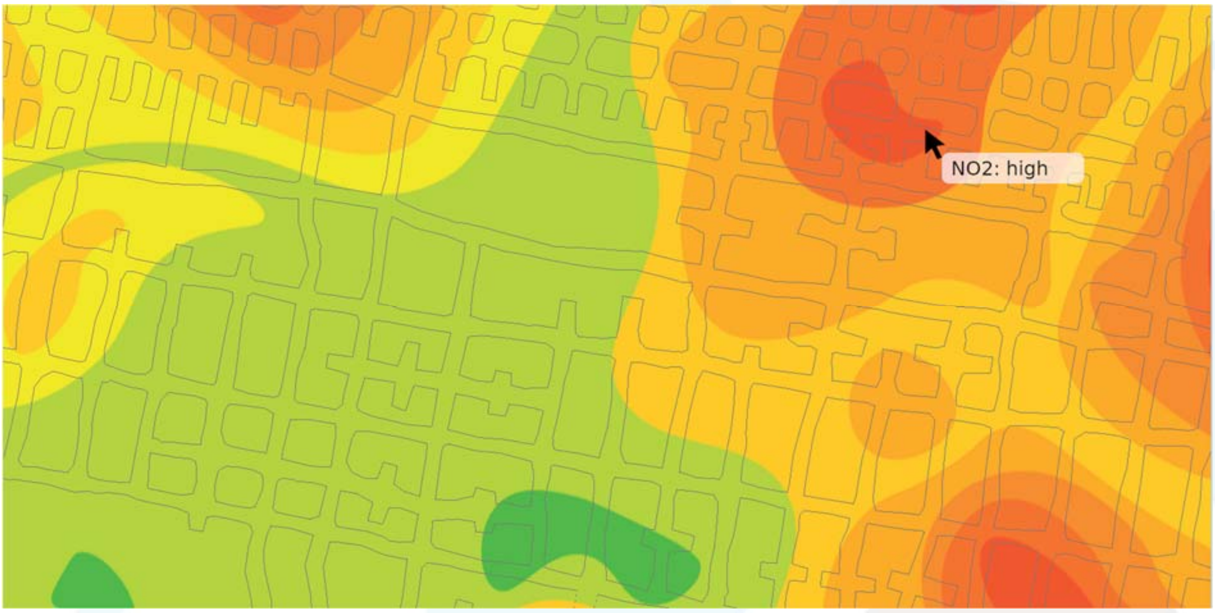

Figure 20: 2D view presented as a heat map.

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2.3 Measurement and analyse while drilling (MWD & AWD)

2.3.1 Measurement and analysing requirements

Recording and analysing drilling parameters (Measuring While Drilling, MWD) collected during the drilling process provide valuable information for production optimisation, potential hazards, determination of the direction of deposit exploitation and overall improvement of the geological, structural and resource model. The information obtained while drilling allows to determine changes in lithology, relevant structural features (discontinuities, joints, faults, etc.) useful for blast design and determination of rook support needs. MWD technology has a significant potential to decrease the lead time between drill and blast cycles, directly translating into cost savings, crucial for the mining industry.

Further to the drill rig-mounted MWD technology, assaying of the drill cuttings in the stope (Assaying or Analysing While Drilling) should allow for a quicker response and decision-making when compared to the default mode whereby rock samples are analysed after drilling. AWD could also help optimise ore stream control and the selection of appropriate blending and processing plant tuning already at the time of drilling, thus long before the ore reaches the processing plant thereby giving more time to optimise the mineral processing.

As part of the *illuMINEation* project, MWD/AWD technology will be tested by two mining companies Minera de Orgiva and RHI Magnesita, both of which are non-metallic mines. The mined ore (i.e. fluorite and magnesite) pose challenges in respect to grade determination as analytical technologies such as XRF or multispectral imaging have difficulties in identifying occurring minerals.

In order to use MWD/AWD technology in the most effective way, it is necessary to determine the exact location of the borehole being drilled and the position of the drill bit in the rock mass. In this way, it is possible to assess where various lithological, tectonic or mineralogical changes occur. Such information allows professionals to carry out a more precise blast design, to update the spatial deposit model in the concerned section and thus update the mine planning. Accurate determination of the location of the drill rig, drill bit as well as systems registering drilling parameters are indispensable for MWD/AWD technology.

Currently, both mining companies where the Use Case tests related to MWD/AWD will take place are preparing to adapt their drilling rigs to MWD technology.

Project results should be suitable for a broader extent of the mining market in the future and must be adjustable to various exploitation profiles and scenarios of different mining companies. Hence, proper systems for efficient mineralogical and/or chemical analysis handling and transfer of data must be prepared.

2.3.2 Data transfer, storage and analysis

The geological deposit model and production planning software needs to be updated quickly with the data derived from MWD/AWD measurements. The simplest method of data transfer is using WiFi networks that are more and more commonly used in mines. As MWD/AWD systems will be installed on or associated with drilling rigs, there is no necessity to minimise power consumption as in the case of intelligent rock bolts. MWD/AWD sensors will operate while boreholes are being drilled and can be powered by the energy generated by the machine's engine.

For less technologically-advanced mines, it would be reasonable to enable data transfer using a data storage device (e.g. a flash drive) which could be used by a drilling operator or geologist in order to copy the data files and update the deposit model via their computer.

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Data derived from MWD/AWD could be stored:

- Locally on the system hard drive installed on the drilling machine,
- locally on a server in the mining company's computer network,
- in the cloud – *illuMINEation* platform.

In all cases it is required to develop a system enabling the visualization and export of measured data to geological modelling, blast design and production planning software.

Regarding data analysis for this solution, it is necessary to create algorithms that correlate the drill bit trajectory and depth intervals with acquired data that informs about geological conditions encountered during the drilling process. This data may include information on probable fractures, zones of looseness or rock hardness (drilling resistance), lithology and mineralization. These algorithms should combine these data and create a borehole model, which can then be incorporated into the orebody model. At this stage, it still needs to be determined if there is a need to use machine learning or artificial intelligence or whether other advanced algorithms may be used. This will likely depend on the amount of data processed and its structure.

2.3.3 Data visualisation

Each deposit is a 3D solid model usually characterised by significant spatial variability in both lithological and ore quality parameters. Therefore, three-dimensional data visualisation is required. Based on that information, geologists interpret and update the deposit model to assess if the newly drilled boreholes are in line with or affect the existing geological interpretation. Access to data visualisation should be available from both mobile devices and desktop computers. Primary users will be geologists, drillers, blasting engineers, foremen or managers working in the mine. In the case of data storage and visualisation via the *illuMINEation* platform, the functionality for importing or uploading of the existing geological, mechanical and structural block model of the deposit needs to be implemented. Most mining modelling software use DXF/DWG file as a most common format for exporting geological model (solids). The block model containing qualitative (resources) data is most often exported in CSV files. Tools for importing DXF/DWG and CSV files and also tools to export CSV (potentially also DXF/DWG) files need to be developed.

In case the data would be stored locally on the machine or transferred to the mine's local network, it is necessary to develop tools for exporting MWD/AWD data to CSV files in order to use them in geological modelling software. These files should primarily contain information about the coordinates of the borehole, its depth, drilling angles, depth intervals of individual observations. See a concept example in Figure 21.

Preliminary (non-binding) sample visualisations of geological and block models as well as a mock-up with information derived from MWD/AWD are shown in Figures 22 and 23.

Collar Table

HoleID	X	Y	Z	Max_depth
XYZ-100				

Survey Table

HoleID	Depth	Dip	Azimuth
XYZ-100			

Assay Table

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HoleID	SampleID	Depth_from	Depth_to	F_occurence	…
XYZ-100					

Lithology Table

HoleID	SampleID	Depth_from	Depth_to	Lithology	Stratigraphy
XYZ-100					

Figure 21: CSV tables needed for geological and block modelling.

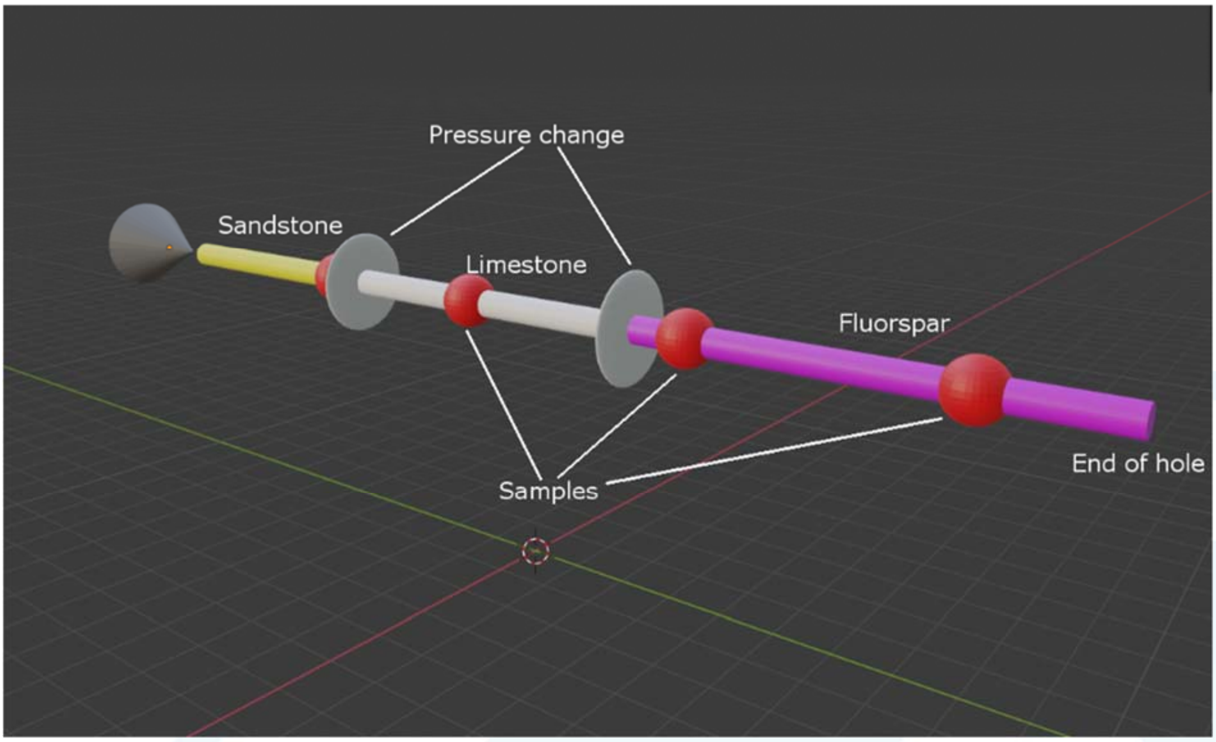

Figure 22: Proposed visualisation of data from MWD/AWD.

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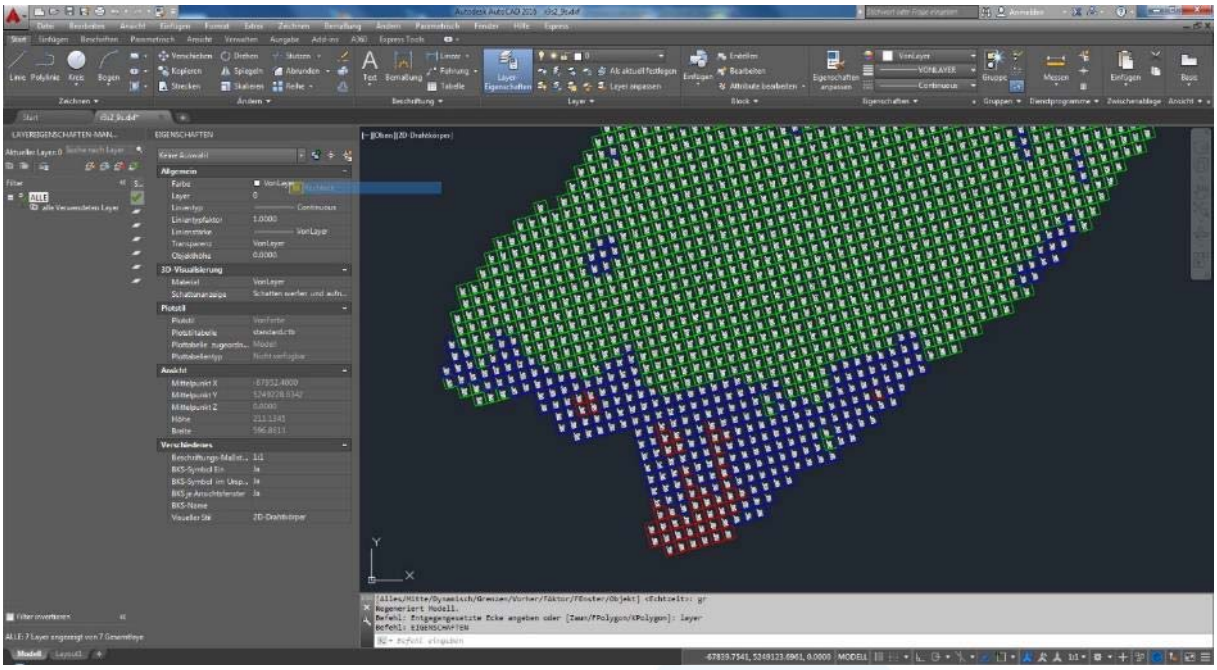

Figure 23: Example of 2d visualisation of block model – RHI Magnesita.

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2.4 Equipment monitoring and predictive maintenance

2.4.1 Monitoring and analysis requirements

Nowadays, working with mining machines belong to the core activities of both open pit and underground mines. It is almost impossible to find a mining company all over in the world where operations are carried out without drilling rigs, loaders or haulage trucks. Hence, reliable and well-maintained mining equipment in good technical condition is of the utmost importance. A system with the ability of monitoring the condition of mining machines as well as predicting possible failures and malfunctions is sought for by mining companies, since maintaining the continuity of exploitation is a key priority in the mining industry. Currently, modern machines are being equipped with many sensors, collecting data about the condition of individual components. Hence, there is the need for the creation of a system that can process the data of these sensors in order to predict possible failures. This way, machine operators or mechanics would be able to prevent malfunctions and order the specific spare parts in advance. In addition to the prediction of failures, such a system would allow for operational improvement.

2.4.1.1 Battery health monitoring

Towards the vision of having safe and green battery-operated mining machines, we propose to focus on novel algorithms for the continuous monitoring of the battery levels (including the minimum prediction of the battery life and battery break down faults) in order to allow the integration of predictive maintenance information, such as battery safeguarding and alert on abnormalities that could lead to a safety risk, a property that was not possible to be developed before with the utilisation of combustion engine solutions.

Thus, one of the project tasks focuses on optimising the performance of batteries, while minimising the overall degradation throughout the battery life. In the first part of this task, a strategy for pro-active predictive maintenance of batteries should be developed. Hybrid models consider traceability and runtime stability, and enable in this way a proactive management of these factors using several approaches:

Work is done on models such as equivalent circuit model-based algorithms (ECM) and electrochemical impedance spectroscopy (EIS). Batteries are usually characterised by individual ageing behaviour. Therefore, investigations will focus on the electrochemical level in order to predict performance and lifetime, accompanied by approaches via prediction or regression algorithms.

The second part of this task will focus on implementation, evaluation and optimisation methods to decide where and when to re-charge the batteries of electric mine vehicles. For this purpose, approximation methods based on constructive algorithms and meta-heuristics will be developed. The algorithms will be based on graph models of mine topologies.

2.4.1.2 Data analytics for predictive maintenance

A high rate of reliability for mining equipment, enabling continuous operation, becomes increasingly important for the mining industry. A machine breakdown due to material failure causes great loss of income due to the production stop. In order to repair the machine quickly, requested spare parts have to be available when needed. The problem is that stocking a large number of spare parts is expensive. The alternative to send spare parts on demand takes time, which creates an even greater loss of income.

A solution is needed for improving the possibility of planning machine maintenance and avoiding breakdown of mining equipment. For that it needs to be possible to predict machine part life span.

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By analysing historical data of exchanged machine parts, it may be possible to detect trends and make estimations of part life span. However, this kind of estimations are rough and sometimes not accurate enough.

Another way to deal with sudden failures could be a system/device for printing spare parts in the mine on site, instead of waiting for their delivery from a warehouse which is located sometimes hundreds of kilometres away or even in another country.

2.4.1.3 Measurement of vibrations on a mining- loader, truck or drill rig

Vibrations and shock cause a vast amount of damages on a mine machine hence shorting the life time of the vehicle.

If the vibration levels and frequencies are known on the mining vehicle, these will give important and useful information on several aspects.

- The vibrations can indicate that a component or part is broken (a shaft, a ball-bearing, a wheel suspension, etc.), or close to a breakdown.
- Bad surface- and road conditions in the tunnel can be detected. A bad surface will shorten the lifetime of the vehicle.
- The mine cycle mode of the vehicle can be determined. Furthermore; the measured values can be used to detect abuse of the vehicle, e.g. scrapping with a drill rig.

Vibrations showing some kind of malfunction can be used as a reliable measurement for predictive maintenance, identifying necessary measures. This will lead to less stop time and improved up time for the hauling or drilling process. The life time of the vehicle will be extended.

The process to determine malfunctions has been used successfully in other businesses, such as paper mills. Thesis projects have shown that e.g a Bosch vibrations sensor in the Epiroc MCG unit can be used to determine what cycle mode the vehicle is in (e.g. diesel engine on, drilling mode, tramming mode etc.).

2.4.1.4 Odometer – Measurement of travelled distance for a mining loader or truck

Autonomous mining vehicles such as loaders and trucks require some kind of measuring of travelled distance. This is often achieved by measuring the revolutions of a drive shaft. The measuring of the number of revolutions is complex because the radius of the tyre will eventually decrease hence providing in correct distance measuring. Environmental impact leads to quickly worn sensor-components as they are heavily affected by mechanical and environmental stress at the same time, while a high level of accuracy is needed.

- A reliable measurement will lead to less stop time and improved up time for the hauling process.
- A reliable measurement of travelled distance is fundamental for reaching a safety classed environment in mixed areas for people and autonomous vehicles in the mine or tunnel.
- A more reliable measurement value than today will improve the overall control loop for an autonomous loader.

2.4.1.5 Tracking and positioning of a loader at a dumping shaft

Current autonomous mining loaders approach a dumping spot very slowly, see picture below. (Figure 24) A barrier- guard or wall is the end stop for the loader, which shall ideally not be reached before dumping. Normally there is a fairly large amount of dust in the air near the dumping spot. Hence, one test shall be an environmental test for durability towards dust.

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If a sensor system can give an accurate position of the loader relative to the barrier wall, this expected to improve the dumping process in terms of decreased operational time as well as increased safety.

Figure 24: Loader at a dumping shaft.

2.4.1.6 Autonomous drone as datalink extender of the mines' WiFi network to a vehicle

When a drill rig, loader or other mine machine are working close to a face or in the very end of the stope or tunnel, it may be lacking WiFi- LTE- or other network connectivity with infrastructure established at a different location of the mine. A drone could serve as data link range extender for data coming from sensing and actuating sources such as intelligent rock bolts, and transport the data to the network further back in the tunnel.

The drone as range extender will ensure that communication between the network in the mine and the sensors, such as a sensor in a rock bolts, or e.g. a loader, can be secured even over large distances. The alternative to lengthen the mine's network would often require human work in unsafe zones. The drone reduces human presence in this risky area.

2.4.1.7 Measurement of articulation angle of a mining loader or truck

The need for autonomous loaders and trucks requires some kind of measuring of the steering angle. The steering is achieved by turning the angle of the joint between front- and rear part of the vehicle. Measuring the angle is complex because it is quickly worn by mechanical and environmental stress. On the other hand, a high level of accuracy is needed for autonomous driving. A reliable and long-lasting measurement will give less stop time and improved up time for the hauling process.

Proposals for alternative measurements to be examined are:

- Two gyros on a loader could be used to calculate the difference in angle between rear- and front parts of the loader.
- Two distance sensors; laser-, wire- encoder or cylinder sensors could be used to measure the distance between rear- and front parts of the loader, one on left side and one on right side respectively. The angle can be calculated from the two measurement values.
- Resolver- sensor and module for calculation of the angle.

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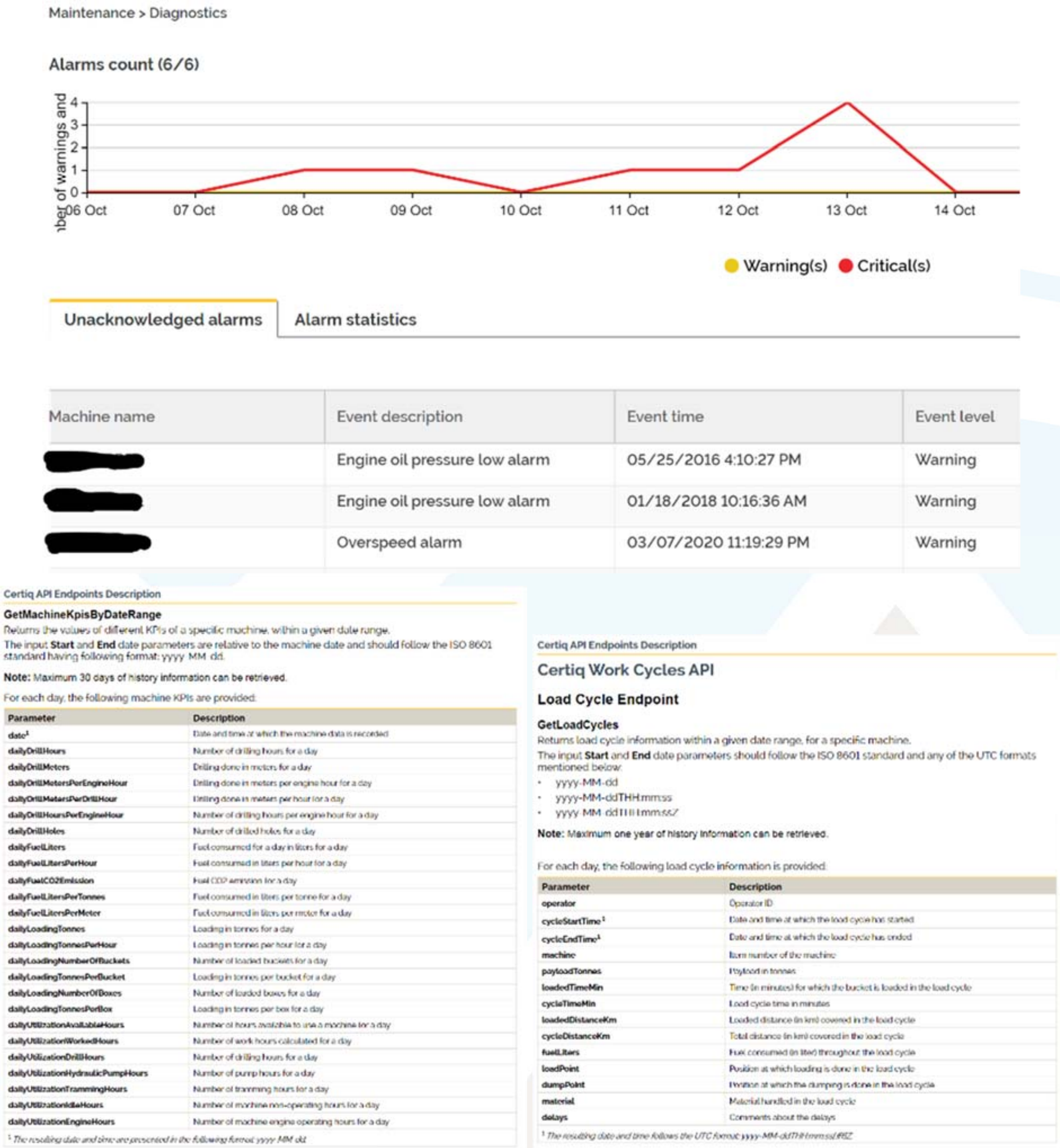
2.4.2 Data transfer, storage and analysis

The easiest way to transfer data is using the WiFi computer network which is installed in the mines, especially since it will also be used for other *illuMINEation* project parts such as intelligent rock bolts or MWD / AWD. Data collection should be performed regularly, every time when the machine enters the garage at the end of a work shift. In addition, data on the machine status should be sent to the database and the warning system, whenever there is a deviation from the correct operation parameters, which may indicate an upcoming problem. In case the equipment has no WiFi connection, data should be obtained offline via a flash drive.

The amount of data transferred and collected during one upload from the machine after the end of the work shift is comparable to the amount of data currently collected in the Certiq system used by Epiroc (Figure 25).



Machine name	Event description	Event time	Event level
[redacted]	Engine oil pressure low alarm	05/25/2016 4:10:27 PM	Warning
[redacted]	Engine oil pressure low alarm	01/18/2018 10:16:36 AM	Warning
[redacted]	Overspeed alarm	03/07/2020 11:19:29 PM	Warning

Certiq API Endpoints Description

GetMachineKpisByDateRange

Returns the values of different KPIs of a specific machine, within a given date range.

The input **Start** and **End** date parameters are relative to the machine date and should follow the ISO 8601 standard having following format: yyyy MM dd.

Note: Maximum 30 days of history information can be retrieved.

For each day, the following machine KPIs are provided:

Parameter	Description
date[1]	Date and time at which the machine data is recorded
dailyDrillHours	Number of drilling hours for a day
dailyDrillMeters	Drilling done in meters for a day
dailyDrillMetersPerEngineHour	Drilling done in meters per engine hour for a day
dailyDrillMetersPerDrillHour	Drilling done in meters per hour for a day
dailyDrillHoursPerEngineHour	Number of drilling hours per engine hour for a day
dailyDrillHoles	Number of drilled holes for a day
dailyFuelLiters	Fuel consumed for a day in liters for a day
dailyFuelLitersPerHour	Fuel consumed in liters per hour for a day
dailyFuelCO2Emission	Fuel CO2 emission for a day
dailyFuelLitersPerTonnes	Fuel consumed in liters per tonne for a day
dailyFuelLitersPerMeter	Fuel consumed in liters per meter for a day
dailyLoadingTonnes	Loading in tonnes for a day
dailyLoadingTonnesPerHour	Loading in tonnes per hour for a day
dailyLoadingNumberOfBuckets	Number of loaded buckets for a day
dailyLoadingTonnesPerBucket	Loading in tonnes per bucket for a day
dailyLoadingNumberOfBoxes	Number of loaded boxes for a day
dailyLoadingTonnesPerBox	Loading in tonnes per box for a day
dailyUtilizationAvailableHours	Number of hours available to use a machine for a day
dailyUtilizationWorkedHours	Number of work hours calculated for a day
dailyUtilizationDrillHours	Number of drilling hours for a day
dailyUtilizationHydraulicPumpHours	Number of pump hours for a day
dailyUtilizationTrammingHours	Number of tramming hours for a day
dailyUtilizationIdleHours	Number of machine non-operating hours for a day
dailyUtilizationEngineHours	Number of machine engine operating hours for a day

[1] *The resulting date and time are presented in the following format: yyyy MM dd*

Certiq API Endpoints Description

Certiq Work Cycles API

Load Cycle Endpoint

GetLoadCycles

Returns load cycle information within a given date range, for a specific machine.

The input **Start** and **End** date parameters should follow the ISO 8601 standard and any of the UTC formats mentioned below:

- yyyy-MM-dd
- yyyy-MM-ddTHH:mm:ss
- yyyy-MM-ddTHH:mm:ssZ

Note: Maximum one year of history information can be retrieved.

For each day, the following load cycle information is provided:

Parameter	Description
operator	Operator ID
cycleStartTime[1]	Date and time at which the load cycle has started
cycleEndTime[1]	Date and time at which the load cycle has ended
machine	Item number of the machine
payloadTonnes	Payload in tonnes
loadedTimeMin	Time (in minutes) for which the bucket is loaded in the load cycle
cycleTimeMin	Load cycle time in minutes
loadedDistanceKm	Loaded distance (in km) covered in the load cycle
cycleDistanceKm	Total distance (in km) covered in the load cycle
fuelLiters	Fuel consumed (in liter) throughout the load cycle
loadPoint	Position at which loading is done in the load cycle
dumpPoint	Position at which the dumping is done in the load cycle
material	Material handled in the load cycle
delays	Comments about the delays

[1] *The resulting date and time follows the UTC format: yyyy-MM-ddTHH:mm:ss[.fff]Z*

Figure 25: Sample screens from Certiq system.

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As for the form and location of data storage, there should be the possibility to store and analyse data both in a system located in the external system (in the data cloud, *illuMINEation* platform or equipment manufacturer), and in the local network of the mining company.

In the case of this solution, it will be necessary to prepare advanced algorithms, machine learning and artificial intelligence, both in relation to the amount of data collected, their diversity and mutual relations between them. Only artificial intelligence, in particular machine learning algorithms can allow for the detection of the early wear of machine components and the prediction of their residual life time or unexpected event. It may be necessary to create reliability models of the specific machine components for difficult operating conditions, possible misuse by operators or exceeding the permitted load ranges, temperatures and levels of operating fluids. The algorithms necessary for this solution will need to "learn" how to detect significant anomalies in different mining conditions (operating context) and analyze several wear patterns of components in order to determine whether or not it is still safe to operate the equipment or service/maintenance is required. What kind of algorithms need to be created and how they will be used will be clarified at a later stage of the project, once it is known what data will be obtained during the work and what analysis can be conducted.

2.4.3 Data visualisation

Visualisation of data related to the condition of machines and their individual parts, as well as possible failures that may occur in the near future, can have a three-dimensional form (Figures 26 and 27). In this form of presentation, it could be possible to rotate the machine at choice, click on various parts and check their wear rate, or zoom to parts marked by algorithms as necessary for servicing or replacement in the near future. Such visualisation could be presented on both mobile devices and desktop computers, depending on the user's needs.

As 3D visualisations usually require devices with higher computing power, it is also reasonable to prepare a user interface in a two-dimensional form, where individual parts of the machines would be presented in the form of flat sketches. It could be possible to switch among these sketches using, for example, the selection list (Figure 28).

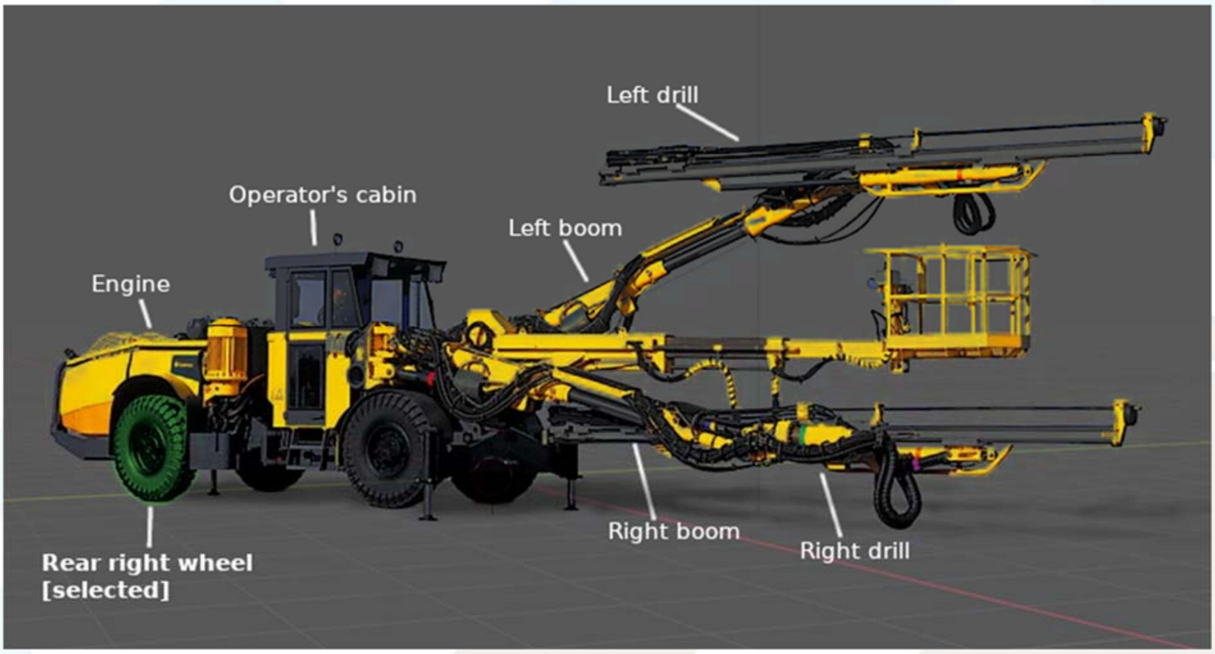

Figure 26: Overall view of a machine in data visualisation system.

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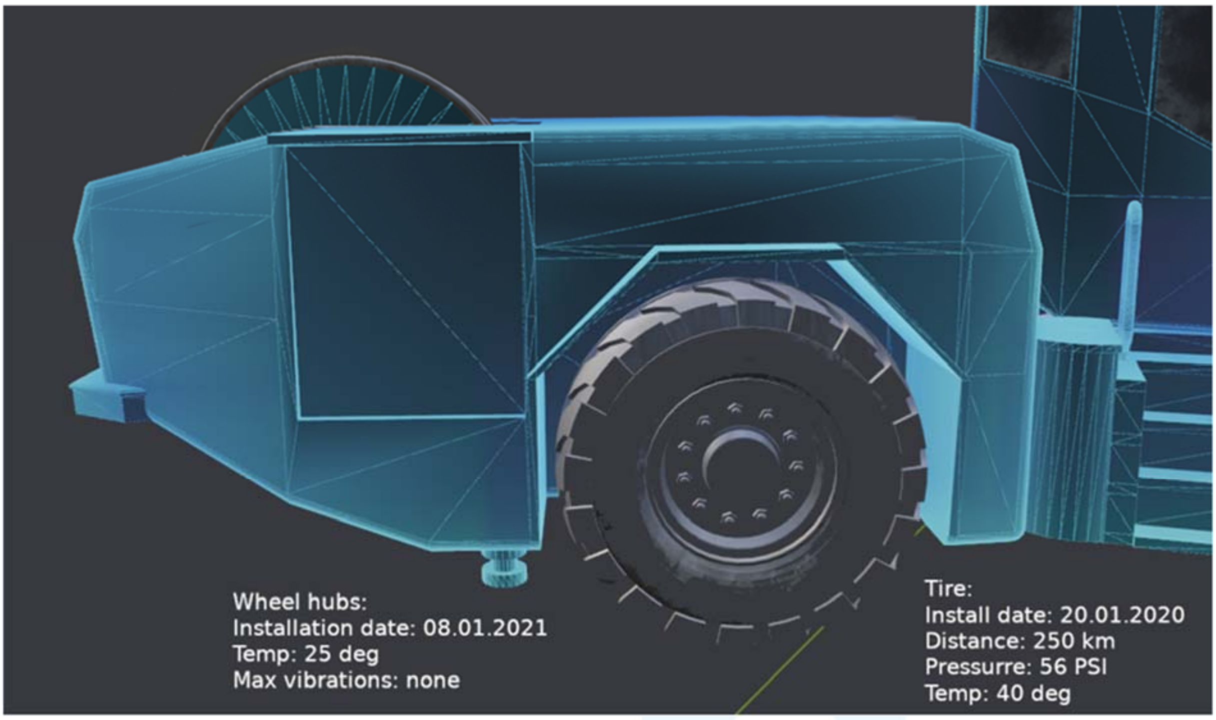

Figure 27: Proposed 3D visualisation of mining equipment condition.

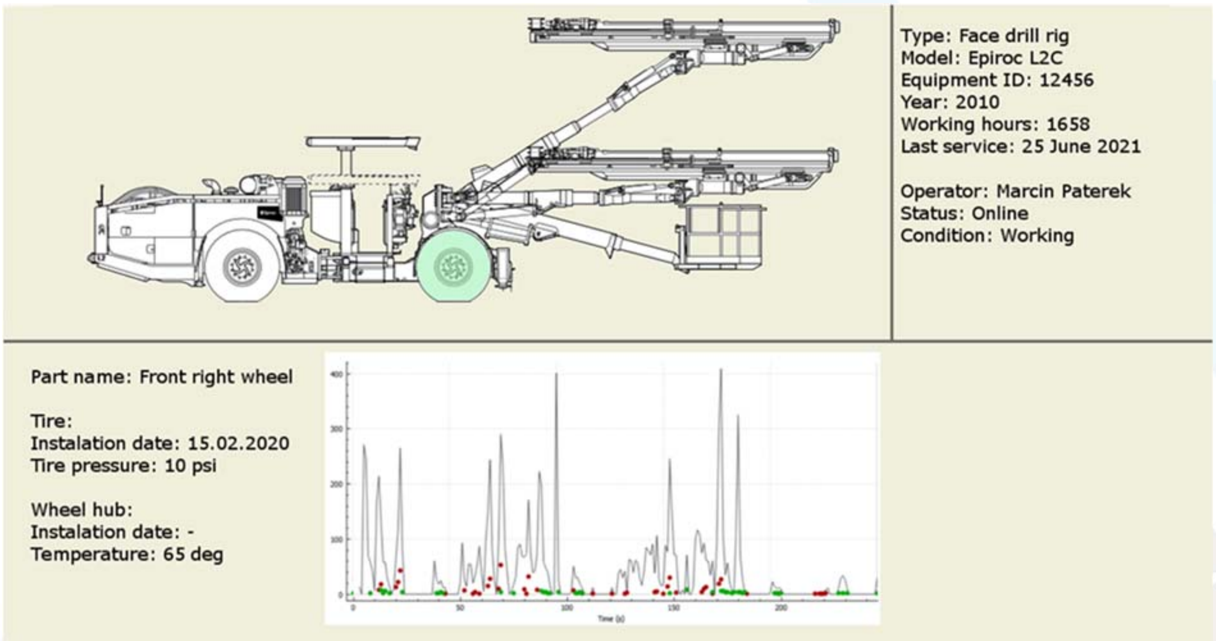

Figure 28: Proposed 2D visualisation of mining equipment condition.

The most technologically advanced way of data visualisation is via goggles for augmented reality (AR), e.g. Microsoft Hololens, which would allow displaying information about the condition of the machine and repairs necessary to make, in the form of information imposed on the real machine image. Although it gives a lot of possibilities, unfortunately, the price of AR goggles is still relatively high, which may hinder its adoption on a larger scale.

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2.5 TSF and environmental monitoring

2.5.1 *Monitoring and analysis requirements*

Referring to groundwater monitoring in the mining areas there is a need for automated measuring device capable of measuring the water level, temperature, electrolytic conductivity and pH. These parameters can clearly indicate that there may have been some impact of the extraction on the groundwater environment. Currently, there are several solutions available on the market for automatic monitoring of water levels and, for example, temperature, but there is none which can measure all the proposed parameters at once. Additionally, currently available devices are not robust enough to work in the environment of highly corrosive mining waters (high salinity or acidity). One of the ideas to increase the resistance of the loggers to the corrosive nature of water and limiting the impact of crystallisation of dissolved components on the quality of measurements, might be the elimination of direct contact of the sensor with the observed liquid.

At this stage it is difficult to determine how these sensors will be powered. The use of batteries is most likely. As most of the measurement points are located outdoors, the use of solar cells might also be possible.

The frequency of groundwater measurements will be determined during tests, although it is assumed that it should not be more often than once a day

Referring to the needs for TSF monitoring data analysis, there are some crucial parameters in TSF structures that should be monitored and analysed. Those parameters are described in the following subsections.

2.5.1.1 Porewater pressure monitoring

To assess the risk of stability failure a constant monitoring system of pore water pressure should be implemented. The water table needs to be monitored as well as pore water pressure in the foundation ground. The water table is usually measured by open-stand pipe piezometers and the pore water pressure in the foundation ground is measured by vibrating wires piezometers.

2.5.1.2 *Open standpipe piezometer*

A standpipe piezometer is a device consisting either of a tube or pipe with a porous element on the end or with a perforated end section surrounded by or wrapped with a filter, which is sealed into the ground at the appropriate level. It is commonly installed in a borehole. The tube of a standpipe piezometer should be of at least 12 mm internal diameter to allow air bubbles to rise freely. Top of the tube should be open to the atmosphere to allow the water level inside the tube to reach equilibrium with the pore water pressure in the ground. The top of the standpipe should be accessible to allow the water level to be measured. This is commonly undertaken via an electric dip-meter, which gives an audible "beep" or light or both when it contacts the water surface. Alternatively, the measurements may be undertaken via a pressure sensor installed at the bottom of the standpipe, whereby the measured pressure relates to the water level.

2.5.1.3 *Vibrating wire (VW) piezometers*

The VW piezometer converts water pressure to a frequency signal via a diaphragm, a tensioned steel wire, and an electromagnetic coil. The piezometer is designed in such a way that a pressure change on the diaphragm causes a change in the tension of the wire. When excited by the electromagnetic coil, the wire vibrates at its natural frequency. The vibration of the wire in the proximity of the coil generates a frequency signal that is transmitted to the

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readout device. The readout device processes the signal, applies calibration factors and displays a reading in the required engineering unit.

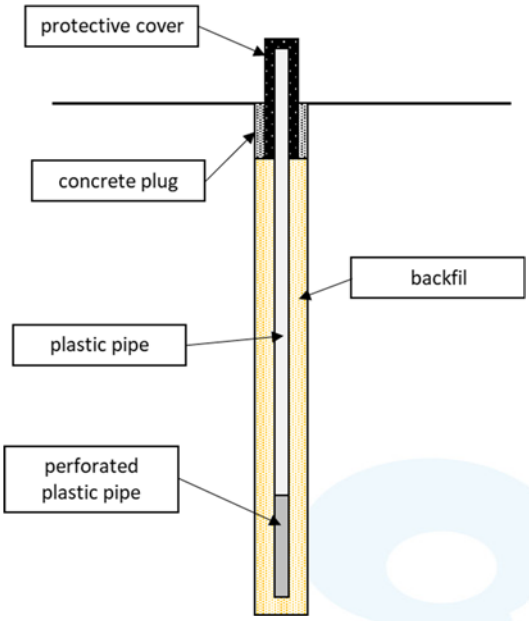

Figure 29: Open stand piezometer construction.

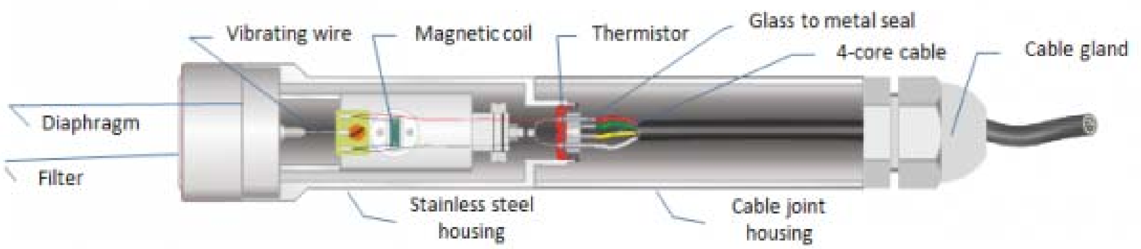

Figure 30: VW piezometer construction.

2.5.1.4 *Displacement monitoring*

There is a need to measure vertical as well as horizontal displacements of the tailings dams. Vertical displacement in tailings deposits are large and are due to compaction from its own weight. The vertical displacements are measured by geodetic benchmarks which are located along the crest of the erected tailings dam. The horizontal displacements are measured in the same points as vertical displacement. All of the benchmarks are aligned in straight lines outside the TSF. The movements of the dams are analysing taking into account both: vertical and horizontal displacements. Within the body of the dam, horizontal movement can be measured by the inclinometers using a probe passing along the pipe. The probe contains a gravity sensor that allows measuring inclination with respect to the vertical axis. The pipe is usually installed in a borehole or in fill. The typical applications of the inclinometers include: determining shear zones in the ground, monitoring the extent and rate of horizontal displacement, monitoring of deflection of bulkheads, piles, or retaining walls. The Figure 31 below shows a typical

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inclinometer body. After the installation the probe is lowered to the bottom and readings are made as the probe is raised incrementally to the top of the pipe, providing data for the determination of the initial pipe alignment. The difference between initial and subsequent readings allows to calculate absolute horizontal deformations at any point along the inclinometer pipe. Measuring the horizontal displacement within the body of the tailings dams and within the ground foundation, potential shear zone where ground material begins to be damaged may be localised.

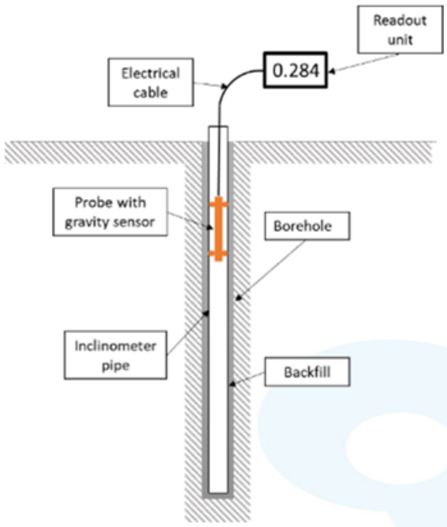

Figure 31: Inclinometer construction.

2.5.1.5 *Monitoring seismicity*

The TSF structures are usually located proximal to the mining facilities where commonly explosives are used to break the rock in order to allow exploit the mineral deposit. In other cases, TSFs may be located in active seismic regions. Due the seismicity, either naturally due to earthquakes or man-made due to blasting, seismic monitoring system is required that is equipped with seismic accelerometers to record the seismic waves. Seismic accelerometers monitor the ground or geological structures for seismic vibrations and, in combination with a suitable recorder, they are termed accelerographs. Most modern seismic accelerometers are of so-called force-balance type (FBA), a servo system in which a feedback force is applied to a suspended inertial mass in order to keep its motion as small as possible. This improves the instrument's linearity and dynamic range. Usually, the mass motion is measured by a sensitive capacitive transducer.

2.5.1.6 *Drainage system monitoring*

In respect of dam stability monitoring, the occurring seepage discharge is the most important factor to be measured. It provides evidence of any serious failure in tailings dams. It is indicative of internal erosion in the dam body with the potential of grave consequences if all necessary countermeasures are not taken in due time. This monitoring should be automated and the readings recorded in the control room without any interruption. It is appropriate to separately register the seepage discharge from each drain and place, so as to be able to determine more easily the location of any increase of seepage and the possible occurrence of erosion.

It is essential for tailings dams to be well-drained in order, to keep the phreatic surface at greatest possible distance from the downstream slope, to reduce pore water pressure, and to

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decrease the danger of liquefaction. The drainage augments the seepage discharge which is much greater than when compared to earth fill dams. However, this is manageable and does not pose any significant danger as long as properly functioning filters and drains are in place, and the seepage is collected and fed back to the tailings pond or the mineral processing plant.

2.5.1.7 *Relief wells monitoring*

Relief wells are used to reduce the pore water pressure in the ground. The TSF structure needs to be considered as a structure that is continuously been expanded, and hence is always in the stage of construction. Consequently, the stress imposed on the ground below is growing all the time, resulting in increasing pore water pressure with the potential of leading to ground failure. Therefore, the pore water pressure should not only be closely monitored but also reduced by appropriate measures as much as possible. As mitigation, relief wells pump the water from the ground and thus reduce the pore water pressure.

Data from all the devices and systems mentioned above should be analysed using machine learning and artificial intelligence in order to establish an early warning system for potential failures and as decision-making support tools in crisis situations.

It should be emphasized that during the project no new sensors for monitoring TSF will be developed, adopted or deployed. All data needed for the analysis indicated here will be aquired from devices already installed on TSF and collected by KGHM. The environmental monitoring mentioned at the beginning of this chapter, conducted with the use of cost-effective sensors will be carried out in the generally understood mining area and in the vicinity of the TSF, but not at the facility itself.

2.5.2 *Data transfer, storage and analysis*

Due to the large number of installed instrumentations for monitoring various aspects of the structures, comprehensive monitoring of Tailings Storage Facilities is complex task. There are several types of sensors featuring different modes of data acquisition. Many instruments collect the data automatically but there are some that still require manual measurements. Another factor that complicates TSF monitoring is because every producer of used instrumentation has its procedure and systems to gather the data. The easiest way to store the data is via a local database with appropriate procedures established, suitable to collect data from all different types of instrumentation. Because the data of some sensors is collected manually, the interaction of humans cannot be replaced.

Data stored in the database should be organised, unified, and normalised prior to further processing and deployment of Machine Learning (ML) algorithms during detailed analysis. Therefore, the process of data collection cannot be fully automatic but the ML algorithms will operate automatically on the pre-processed data.

The amount of the data is estimated based on the experience of the management of Żelazny Most, representing one of the largest TSF in the world (chapter 2.1.3). The dataset shown in Table 2 is closely monitored.

Taking into account the amount of data collected as part of TSF monitoring, it is necessary to use machine learning to develop the advanced analytical models for its analysis. These data are also characterized by a multitude of monitored parameters and the multivariate relationships existing between them. That is why it is so important in this case to use advanced analytical techniques. It seems necessary to prepare algorithms to detect shear zones on the basis of inclinometer or benchmark readings as well as development of ML model for shear wave velocity determination and mechanical properties of rocks. A tool enabling automatic soil classification based on data from Cone Penetration Test probes and tools supporting the creation of digital models of geotechnical layers would also be useful. Similar to all the previously mentioned solutions in this report, at this stage of the project it is difficult to

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determine exactly which algorithms or ML/AI solutions should be finally selected to implementation. Those listed here are only a first suggestion.

With respect to environmental monitoring, where measuring devices are distributed across a large area, the best method for data transmission to the mine network and databases appears to be the use of GSM cellular telephone network or the LoRa communication standard. The latter option would not generate additional costs related to telecommunication charges, but however, it would probably be necessary to establish a network of relay stations. It needs to be remembered that the proposed measuring devices developed in the course of *illuMINEation* are supposed to be available at relatively low costs allowing for sensor and device installation on a large scale. If GSM networks would be used for data transmission, significant charges would result as for each of the devices, an individual SIM cards would be required. This would likely hamper the mass-deployment of such IIoT devices by future end-users.

Table 2: List of devices, parameters and observations frequency at the Żelazny Most.

Instrumentation	No. of sensors	Type of data	Type of measurement	Frequency of data collection
Drainage wells	54	location (X,Y,Z)	manual	once
		Discharge	manual	twice a month
		Water table in the well	manual	twice a month
		Suspended solids content	manual	quarterly
		Chloride content	manual	quarterly
Relief wells	116	location (X,Y,Z)	manual	once
		Discharge	manual	twice a month
		Water table in the well	manual	monthly
		Suspended solids content	manual	quarterly
		Chloride content	manual	quarterly
Geodetic Benchmarks	513	Location (X,Y,Z)	manual	quarterly - half-yearly
	36	Location (X,Y,Z)	automatic	continuous
Inclinometers / Automatic inclinometers	70 / 8	Location (X, Y, Z)	manual	once
		Displacement (X, Y) measured every 0.5 m of the profile	manual / automatic	quarterly – yearly/ continuous
Open standpipe piezometers	1739	Location (X,Y,Z)	manual	once
		Water level	manual / automatic	twice a month - quarterly / hourly
VW piezometers	347 / 83	Location (X,Y,Z)	manual	once
		Porewater pressure	manual / automatic	monthly / hourly
Seismic sensors	28	Location (X,Y,Z)	manual	once
		Acceleration (X,Y,Z)	automatic	continuous

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2.5.3 Data visualisation

Data visualisation systems should be developed and designed in such a way as to easily couple measured data with particular spatial sensor location (X,Y,Z). The location of the sensor should be shown on a map with easy access to recorded data. Practically all measured values should be plotted in relation to time therefore simple one-dimensional diagrams would be sufficient. The early warning system based on the outputs of data processing and analysis should be developed and implemented in the visualisation tools of the *illuMINEation* IIoT platform. Warnings about exceeding the threshold values could also be sent automatically via SMS or email to predefined recipients This applies to both TSF and the environmental monitoring.

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3 Conclusions

The needs, requirements and solutions presented in this report represent only a small part of the mining industry's safety and operational optimization needs. Although they were defined by only four mining companies and one machine manufacturer, they can be easily transferred into other companies within this industry sector.

The use of the intelligent rock bolts proposed in this report will certainly follow into improved safety in underground mining works, both due to the possibility of monitoring the rock mass and the atmosphere in the excavations.

The MWD / AWD technology will allow the mining companies to make faster decisions about the direction of exploitation, improve blast design, the need to use or the type of roof support or the selection of ore processing technology. These elements influence directly the work efficiency and operating costs.

Likewise, the proposed technologies for predicting failures / repairs of mining machines (predictive maintenance) will significantly affect the efficiency of work, significantly reducing downtimes for necessary repairs and improving management of machinery park.

Devices for monitoring the quality of groundwater and monitoring the impact of mining operations on groundwater translate directly into the safety of the natural environment, and in the case of observations of undesirable phenomena, into quick start of preventive actions.

The algorithms proposed in this report to support TSF monitoring will also allow for a faster reaction at the moment, for example, of observation of symptoms of dam instability, which will help to prevent the failure/damage. Thus, it is possible to ensure greater safety for the environment and the population living in the vicinity of TSF.

During the Work Package 2 workshops and thus during the preparation of this report, the use case partners refined their needs in relation to the solutions needed to be developed within the project. They described the environmental conditions in which the devices will have to operate, what threats occur in their mines and technical conditions such as possible data transmission methods or mining equipment they use in their operations. In this report, partners also specified examples of data collection, processing and visualization as well as export to other software. This report also clarifies many aspects of what is to be observed e.g. what components of the mine atmosphere should be monitored or that it is important not only to observe condition of the rock mass, but also whether the anchor fulfils its role. This report is a significant extension of the original assumptions described in the project proposal. Use case partners are aware that the final form of the project outcomes may differ from the solutions presented here, due to technical or software limitations but they believe that solutions will meet most of the identified requirements.

The solutions proposed by the *illuMINEation* consortium will not make mining and mining-related operations completely safe, but they will certainly improve the state of safety and have a positive impact on the modernization of this sector. In order to fully use the potential of the proposed devices, their construction must be modular, so that they can be easily adapted to the characteristics of a particular mine or deposit. Some solutions, such as intelligent rock bolts, should be low cost so that mining operators will be willing to use them in large numbers, because only then they will fulfil their purposes.

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