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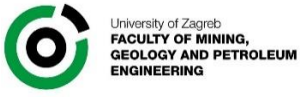

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Prospections of former deposits for the purpose of protection of mining and cultural heritage

DIM-ESEE Conference
15th – 17th October 2025, Dubrovnik, Croatia

Ana Maričić[1*], Zlatko Briševac[1], Vladislav Brkić[1]
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Presenting author: Ana Maričić

Keywords: Prospection, raw materials deposits, mining heritage, cultural heritage, geotechnology

Abstract

The importance of scientific prospecting of former raw material deposits in connection with the protection of cultural heritage is becoming increasingly important. From a geological and mining point of view and depending on the objectives pursued, research can be divided into two types. The first is the exploration of sites where various mineral raw materials were once mined, the second is the restoration of buildings and objects with cultural significance. In the second case, the focus is more on the properties of the material used in construction, as an adequate substitute must be found. While in the first focus is given to the determination of reserves content in the deposit and possibility of its exploitation. In this article, both types of research are presented in Croatia, where many types of mineral raw materials used to be mined. In addition, buildings are currently being restored after the earthquake in Zagreb, so the need for authentic materials is great.

In Croatia, there are sites that represent a potential for geotechnological heritage (**Briševac et al., 2021a, Briševac et al., 2021b**). Such heritage is mostly located in the more touristically attractive part of the country (**Figure 1**) near the Adriatic Sea. The quarrying and use of natural stone for building purposes is very present in all Mediterranean countries (**Calvo & Regueiro, 2010**), including Croatia, where carbonate stone was mainly used (**Briševac et al., 2021b**). This type of stone is still the most commonly quarried today (**Briševac & Bohanek, 2023**, **Briševac et al., 2023, Figure 2**), but its susceptibility to wear and tear due to weather and temperature influences must be taken into account when using it. More and more old buildings need to be renovated and the original stone should be used, but various obstacles are encountered (**Maričić et al., 2023**). The natural stone was quarried along the Adriatic coast from Istria through Dalmatia to Dubrovnik, especially on islands of Brač and Korčula as well in the inland (**Donelli et al., 2009**). The knowledge of quarrying activity in ancient Histria and Dalmatia amounts to the larger economic and cultural centres of the provinces. From these we learned about the highly developed construction and artistic techniques used at that time. On the eastern Adriatic coast, we come across antic monuments built of local stone. Stone from each individual quarry has its own characteristics and quality (**Buzov, 2009**).

The aim of this paper is to present the particularities of the research methodology carried out with the purpose of preserving the memory of the activity and the places where mineral resources were once extracted, as well as the problems encountered in the restoration of historic buildings.

The research methodology consists of studying the available literature on the past exploitation of mineral resources. Various databases, previous publications and geological maps are reviewed and a field inspection of the sites is carried out, which includes the preparation of photographic documentation and, where appropriate, the taking of samples. When investigating the restoration of historic buildings, stone samples are taken from the building itself and processed in the laboratory to determine the geological and physical and mechanical properties (**EN 1926:2006; EN 1936:2006; EN 13755:2008; EN 12440:2019; EN 12407:2019; EN 12670:2019**).

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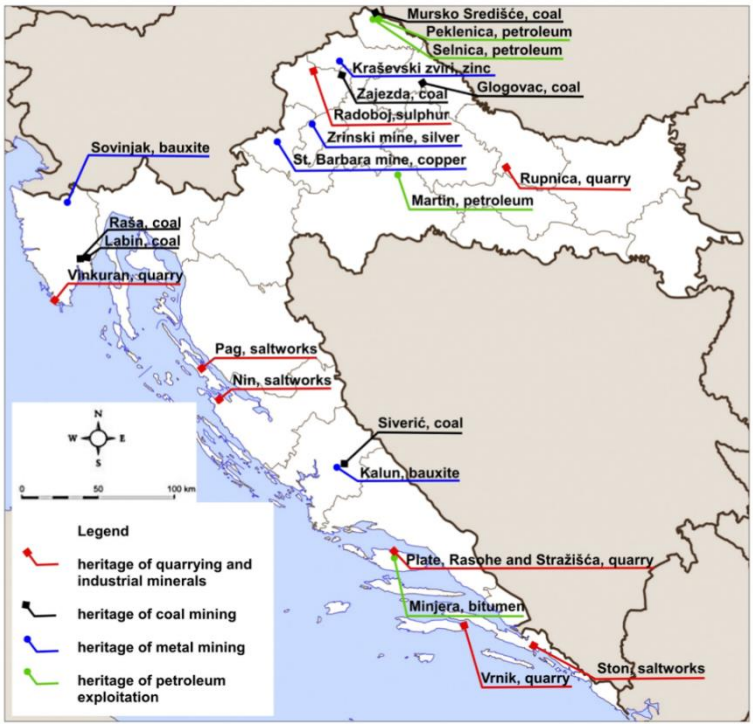

Figure 1. Map of former mineral raw materials exploitation in Croatia (**Briševac et al., 2021a**).

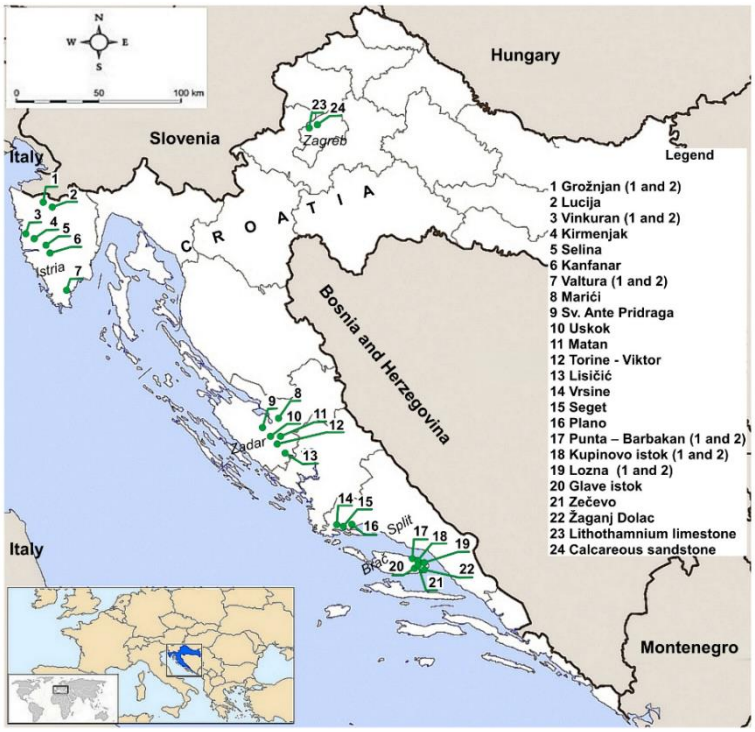

Figure 2. Some of the more famous natural stone varieties in Croatia (**Briševac et al., 2023**).

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Ana Maričić (assocoate professor): conceptualization, investigation, data curation, methodology, writing – original draft and writing – review & editing. **Zlatko Briševac** (assocoate professor): conceptualization, data curation, formal analysis, investigation, methodology, project administration, resources, supervision, validation, visualization, writing – original draft and writing – review & editing. **Vladislav Brkić** (assocoate professor): conceptualization, supervision, validation, writing – review & editing.

All authors have read and agreed to the published version of the abstract.

Albania as a strategic project partner under the EU critical raw material act

DIM-ESEE Conference
15th – 17th October 2025, Dubrovnik, Croatia

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Presenting author: Prof.Dr. Përparim Alikaj

Keywords: Raw Material, CRM, Exploration, Strategic Partner.

Abstract

Albania possesses a uniquely diverse and abundant endowment of mineral resources, with more than 50 identified types, including oil and gas, tar sands, chromium, copper, lateritic nickel, titanomagnetite, phosphorites, bauxites, silicon, and coal. Within this spectrum, a number of critical and strategic raw materials stand out, such as copper, lateritic nickel and cobalt, silicate nickel, titanomagnetite (titanium and vanadium), zinc, lithium, phosphorite, bauxite, silicon, and gold, as well as promising prospects and showings of PGE, manganese, magnesium, barite, zirconium, fluorite, radioactive minerals and rare earth elements. Chromite, historically Albania's flagship mining commodity, continues to retain global criticality in supply chains.

This mineral richness is rooted in Albania's favorable geological setting, positioned in the Tethyan ophiolite island-arc belt of the Western Balkans, which covers a total surface area of 4,000 km^2 (Meco and Aliaj 2000). The numerous mountain rivers and creeks play the role of natural enrichment plants, taking for million of years the altered minerals of various grains, from highlands to the plains as river and marine placers of important minerals and metals like, rutile, monazite, zircon, chromite, titanomagnetite, magnetite, gold, ilmenite, garnet, platinum, etc. The plains in the pre-Adriatic depression also contain numerous concentrated buried marine/river placers which are under-explored so far.

The Government of Albania has shown its commitment towards innovation in raw materials through the establishment of the EIT Regional Innovation Centre in Elbasan. Adequate research infrastructure and equipment are currently not available for researchers and innovative SMEs in the sector. The lack of integration with the EU industrial value chains and the absence of a strong network between the sector public and private partners hinder innovation efforts in the sector.

The privatization process continued with the approval of the Law "On Concessions", and giving by concession of certain parts of mining industry (of this branch).
The mining objects given in concession so far, are as below:
• Bulqiza chromium mine and ferrochrome smelters of Burrel and Elbasan cities;
• Chromium Mines in Kalimash, Kukes district and Kalimashi dressing plant;
• Munella, Lak Rosh Karma 2 copper mines and also the copper dressing plant in Fush Arres town;
• Selenica Bitumen mine, Vlora district and its bitumen smelter.

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During the communist era, Albania was an intensive producer of chromium, copper, lateritic nickel-cobalt, coal, oil, and gas, ranking third globally in chromium output, with a production capacity of up to 1.4 million tons per year. The copper industry was in a closed circle, from exploration, mining (about 1.2 million t/y), processing, smelting, refinery and electric cable production. In addition to copper, other important precious elements like gold, silver, selenium, tellurium etc. were obtained in the refinery. Lateritic iron-nickel-cobalt and nickel silicate were important minerals, initially exported as raw minerals abroad and later being processed in Albania to produce cast iron, steel, nickel and cobalt. The maximum mineral mining output was reached by mid 90^s, with 1.18 million t/year.

Nowdays, the mining sector is given to private sector and is driven by private enterprises, with chromium, copper and iron – nickel dominating extraction, while copper and chromium concentrates, along with ferrochromium, remain the country's principal export commodities. In **Table 1** are shown the main commodities actually being mining out in Albania in the period 2021 – 2024.

Table 1. Main minerals production in Albania for the period 2021 – 2024

Mineral	Mineral composition	Mineral extraction the last four years in ton			
Type	(%)	2021	2022	2023	2024
Chromite	Cr_2O_3 (15-48); FeO (10-12,5); SiO_2 (11-18); MgO (23-27); Al_2O_3 (7-9)	650,200	932,686	920,770	952,589
Iron-Nickel	Fe (38.5-47,2); Ni (0.9-1,1); Co (0.06-0,08); SiO_2 (7,1-17); Cr_2O_3 (3.1-4.6)	427,650	174,918	63,131	5,280
Nickel silicate	Ni (1,07-1,32); Fe (14-18); Co (0,045); SiO_2 (37-39,7); Cr_2O_3 (3.3-8.5)				
Copper	Cu (1.35-1,85) average 1.6	618,518	641,245	460,628	829,644

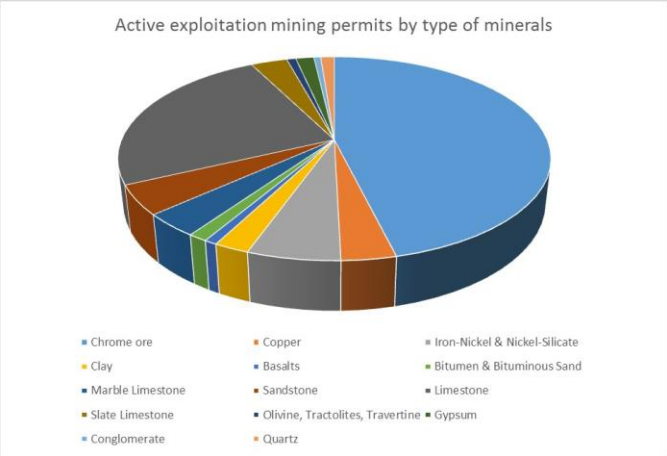

Figure 1. Active exploitations mining permits by type of minerals

Regarding the CRM, Albania holds untapped potential to become a strategic partner under the EU Critical Raw Materials Act. Substantial reserves of lateritic iron-nickel-cobalt (over 350 million tons) and titanomagnetite (over 130 million tons) constitute long-term, sustainable sources of critical minerals of direct relevance to European industrial resilience. Unlocking this potential, however, requires scaling exploration, expanding mining activity, and investing in domestic processing capacity to align with EU supply chain security objectives.

In this context, Albania is strategically positioned to reinforce Europe's secure and diversified supply of critical raw materials. By leveraging its mineral potential and aligning with EU innovation and sustainability standards, Albania can transform into a key partner in implementing the Critical Raw Materials Act, advancing both regional development and European strategic autonomy.

The Albanian Government has already demonstrated increasing attention to this sector through several key instruments. The Smart Specialisation Strategy (S3) 2024–2030 explicitly identifies *renewable energy and natural resources* as one of its three national priority domains together with agriculture and tourism, thereby embedding mining and raw materials within a forward-looking innovation policy . The legal and strategic mining framework needs to be updated to align to the latest Critical Raw Material Directive and make the country attractive for investments. The mining strategy of the country expires in 2025. It was prepared almost 15 years ago in a different context. The Government of Albania

by its Decision No. 479, dated 29.6.2011 approved the **Mining Strategy for 2010-2025**, which orientates the development of the mining industry in Albania. The strategy acknowledges the size and importance of the EU for the mining sector in Albania and urges for the orientation of the sector towards the EU demand especially for critical materials. The strategy also has listed the **reassessment of the mineral resources in the country with modern technology** as a necessity while encouraging **the recycling and reuse of the mining waste.**

More specifically relevant key objectives of the strategy include:
a) Development of investments through the promotion of domestic and foreign investments, legal and regulatory improvements, reduction of administrative barriers, strengthening of institutions related to the mining business.
b) Development of environmentally friendly mining activities by implementing mitigation measures, environmental rehabilitation processes, and strengthening oversight and monitoring to ensure workplace safety, reduce harm and environmental pollution, and apply advanced technologies to minimize as much as possible the effects on the lives of communities and nature.
c) Consideration of social aspects through the inclusion of the community in discussions and decision-making, increasing transparency, broader involvement of civil society, assessing the benefits and damages to the community as an approach to enhance well-being, employment, opportunities for infrastructure improvement, and the healthcare and education system, especially in economically underdeveloped areas.

Law No. 10 304, dated 15.7.2010 "On the mining sector in the Republic of Albania", as amended[1] is the main legal basis for mining activities. The law determines the strategy as the fundamental document outlining the development priorities for a 15 year period. The strategy becomes operational through medium-term 3-year action plans. The latest action plan was approved in 2022[2].

A new strategy taking into account the need to align with and take advantage of the opportunities offered by the CRM Act needs to be prepared. Complementing this, a dedicated Roadmap on Critical and Strategic Raw Materials is underway, led by the EIT RawMaterials Regional Innovation Center in Elbasan, in cooperation with the Albanian Geological Survey (AGS) and the National Agency of Natural Resources (AKBN). This Roadmap aims to consolidate geological data, assess market potential, and structure investment opportunities in line with the EU Critical Raw Materials Act.

Short problem analysis

Albania has a longstanding history in mining with significant mineral deposits of chromium, nickel, copper, coal, limestone, etc. Geological studies discovered substantial deposits of chromium ore, ferronickel, copper, titanomagnetite, polymetals, bauxite and non-metallic minerals such as phosphorite, magnesite, limestone, decorative stones, etc. Mining and quarrying accounted for 2.2 % of GDP in 2021 and for 11.4 % of total exports in 2022[3].

Studies of mining reserves and maps are all dated prior to 1990[4].This represents a major burden for attraction of international investors in the sector. There is an urgent need to undertake new assessments with advanced technologies to reassess the reserve potential for minerals especially CRM/SRM.

Extractive and processing waste could serve as secondary sources for CRMs, but an assessment of the historical and current waste is not available.

The Government of Albania has shown its commitment towards innovation in raw materials through the establishment of the EIT Regional Innovation Centre in Elbasan. Adequate research infrastructure and equipment are currently not available for researchers and innovative SMEs in the sector. The lack of integration with the EU industrial value chains and the absence of a strong network between the sector public and private partners hinder innovation efforts in the sector. This strategic framework enhances geological surveying through a unified, standards-aligned digital data platform, while promoting advanced exploration and processing techniques alongside industrial symbiosis. It integrates renewable energy, AI/IoT monitoring, and digital permitting into mining operations, and strengthens human capital by synchronizing academic and vocational training with CRM innovation needs. Through the establishment of open infrastructure for research, resilient supply-chain development from upstream extraction to downstream integration, and

[1] Amended by Laws No. 9/2013, dated 14.2.2013, No. 134/2014, dated 9.10.2014, No. 68/2019, dated 9.10.2019, No. 65/2021, dated 20.5.2021,
[2] DECISION No. 380, dated 1.6.2022, "On the approval of the 3-year action programme for the years 2022-2024, in implementation of the mining strategy".

[3] INSTAT 2023.
[4] "Extractive Industries Transparency Initiative in Albania Report for the years 2017 and 2018", December 2020.

adherence to circular-economy practices. By leveraging European funding instruments such as IPA III 2025-2027, KAVA funds and private investment, it supports both the country's sustainable growth and the resilience of regional CRM supply chains. Given that reserves of traditionally exploited minerals such as chromium and copper are approaching depletion, Albania's future lies in systematic exploration and modernization. The EU could play a pivotal role in supporting Albania through advanced exploration technologies, ranging from remote sensing and airborne surveys to ground-based geophysics and high-resolution rock sampling in certified labs. A nationwide airborne geophysical survey, capable of reaching exploration depths beyond 1,000 meters would radically accelerate the new discoveries process, reduce exploration timelines by up to two orders of magnitude, and attract credible long-term investors.

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Geological and economic evaluation of ore deposits suitable for Narrow Reef mining Equipment

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15th – 17th October 2025, Dubrovnik, Croatia

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Presenting author: Ema Vokić

Keywords: narrow reef mining, NRE-suitable ore deposits, stratiform, stratabound, mining efficiency.

Abstract

This study investigates the geological, operational, and economic parameters that define the suitability of various ore deposits for extraction using Narrow Reef mining Equipment (NRE) – a mechanized mining system designed for thin (≤1.7 m), subhorizontal (dip ≤22°) ore bodies. These deposits often remain uneconomic when using conventional mining methods due to excessive dilution, safety hazards, and reduced ore recovery (**Bohanek et al., 2023**).

The research area encompasses a global selection of stratiform and stratabound deposits in diverse tectonic settings, including layered mafic-ultramafic intrusions, intracratonic sedimentary basins, and synvolcanic environments. The evaluated volumes include over 285 deposits across Africa, Europe, North America, Asia, and Australia.

Data sources include published geological surveys, mining reports, and peer-reviewed literature. Deposits were categorized into four major groups: (1) magmatic (Ni-Cu-PGE) sulfide deposits, (2) sediment-hosted stratiform copper (Cu) deposits, (3) paleoplacer gold (Au) reefs, and (4) volcanogenic massive sulfide (VMS) deposits. Morphological parameters such as ore thickness, dip, lateral continuity, and host lithology were quantified. Analytical methods involved GIS-based screening, geological correlation, and economic evaluation of mechanized extraction studies.

Geological analysis shows that NRE-compatible magmatic PGE reefs occur within the Bushveld Complex (South Africa), Great Dyke (Zimbabwe), Stillwater Complex (USA), Munni Munni (Australia), and Skaergaard Intrusion (Greenland). These intrusions display up to 2 m thick mineralized horizons rich in PGE, Ni, and Cu, hosted by pyroxenite, norite, and chromitite layers, with dips between 5° and 20°. Similarly, stratiform Cu-Ag deposits in the Kupferschiefer Formation (Europe) and Central African Copperbelt exhibit thicknesses up to 2 m, gentle dips (<25°), and mineralization hosted by organic-rich shale, sandstone, and carbonate sequences.

Paleoplacer Au reefs of the Witwatersrand Basin meet the morphological criteria, with most active and historical mines exploiting quartz pebble conglomerates <2 m thick. A minority of VMS systems, such as Yushui (China) and Sulitjelma (Norway), include stratiform sulfide zones suitable for NRE, though VMS deposits are generally excluded due to post-depositional structural complexity.

Results of the comparative analysis between NRE and conventional mining methods indicate that NRE achieves (**Dludlu et al., 2021; Bohanek et al., 2025**):

- Ore recovery up to 90 %, with reduced dilution by up to 19 %,
- Increased safety through remote operation and reduced underground workforce (up to 70 % less),
- Higher productivity (up to 4,000 m²/month),
- Lower operational costs despite higher capital investment, and

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- Improved profitability, especially in high-grade PGE and Cu systems.

The study concludes that NRE technology significantly enhances the technical and economic viability of mining thin, subhorizontal ore bodies. These findings have implications for optimizing mine design, extending the life of marginal deposits, and improving the sustainability of underground operations.

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Author's contribution

Ema Vokić (assistant): formal analysis and original draft and writing. **Sibila Borojević Šoštarić** (professor): conceptualization and methodology. **Vječislav Bohanek** (associate professor): conceptualization, review and editing.

All authors have read and agreed to the published version of the abstract.

Critical Raw Materials in Croatia: Geological Context and Identified Prospects

DIM-ESEE Conference
15th – 17th October 2025, Dubrovnik, Croatia

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Field	
Raw materials prospection and discoveries	x
Mining methods	
Geometallurgy and sustainable extraction	
Materials recycling and waste management	
Raw materials education	

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Presenting author: Erli Kovačević Galović

Keywords: critical raw materials (CRM), mineral deposits, geological potential, Croatia, historical mining.

Abstract

Geological reconnaissance and the systematic collection of data on the occurrences of mineral deposit across the country represent an ongoing task of the geological survey, carried out in cooperation with academic institutions and the mining industry. In Croatia, a fundamental role in this process is played by the Croatian Geological Survey (HGI-CGS) operating as the geological survey under the supervision of the Ministry of Science, Education and Youth. HGI-CGS creates "Map of Mineral Resources of the Republic of Croatia", conducts independent prospecting studies, verifies new deposits and occurrences using existing legacy geological maps in small scales, geochemical and geophysical data. The database on mineral resources formed in this way serves as a spatial basis for creating a unique information system of mineral resources, and it aims to be adapted to the INSPIRE directive of the European Commission. Based on these data, maps of the potential of mineral resources are created at the national level, which serve as a basis for spatial planning. The results of these works carried out for over 115 years are >30.000 unpublished reports and studies.

Mining sector within Ministry of Economy is responsible for mining concessions, archives geological documentations made by mineral companies, and maintains publicly available Unified Information System of Mineral Raw Materials (JISMS), which includes a register of exploration and exploitation fields, a list of mining companies, a record of all demands for exploration and exploitation fields, as well as a balance sheet of mineral reserves.

The combination of the above databases at the level of the Republic of Croatia assists many sectors such as mining and industry by providing them with a vast geoscientific knowledge.

Critical raw materials (CRMs) are essential components in a wide range of advanced technologies and strategic industries, playing a key role in the green and digital transitions, as well as in defense and aerospace applications. Ensuring a secure and sustainable supply of these materials has become a strategic priority for the European Union **(European Commission, 2024).**

Although the Republic of Croatia has not historically been considered a significant source of CRMs, its diverse geological structure suggests moderate but notable potential for certain CRM deposits. The country lies at the intersection of the Pannonian Basin and the Dinarides, each characterized by distinct lithological and structural features. As a result, the geology is complex and varied, comprising magmatic, sedimentary, and metamorphic formations that host a variety of mineral occurrences. These conditions have led to localized accumulations of several CRMs, most of which are found in regions such as Slavonia, Lika, Kordun, Gorski Kotar, and Istria.

Documented occurrences include graphite, barite, bauxite (containing rare earth elements and gallium), magnesium-rich dolomites, copper, and possibly feldspars and lithium within pegmatites. Past mining operations have confirmed substantial graphite zones in Psunj, Papuk and Krndija **(Jurković, 1962),** while the most notable barite deposits are located on Petrova Gora, in Gorski Kotar, and in Lika. Copper ore and other metals were mined for centuries in the

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Trgovska and Petrova Gora areas, known for significant reserves and rich ore grades **(Borojević Šoštarić et al., 2009).** Although mining ceased in the mid-20th century, geological formations indicate potential for further copper exploration. Bauxite deposits are widespread throughout the Dinaridic karst region; many have been exploited, but numerous occurrences remain, some with considerable rare earth element (REE) concentrations **(Kovačević Galović et al., 2025).** Dolomites are abundant in Croatia's karst region and, due to their high purity, represent a valuable raw material for magnesium production **(Šoštarić Borojević et al., 2025)**. Pegmatite occurrences have been reported mainly in the Psunj and Papuk regions, but they are poorly studied and require further investigation **(Jurković, 1962).**

Although modern systematic exploration of critical raw materials (CRMs) in Croatia has largely been absent since the mid-20th century, historical mining records and archived geological data provide a valuable foundation for assessing the country's mineral potential. The Croatian Geological Survey contributes to this effort by maintaining a national database of mineral deposits and occurrences (**Figure 1**), compiling and updating geological and metallogenic maps, and reassessing historical geoscientific data **(Miko et al., 2020).**

While Croatia's overall geological potential for CRMs is limited compared to more resource-rich regions, the presence of selected materials and a foundation of historical data present good opportunities for further research and focused exploration.

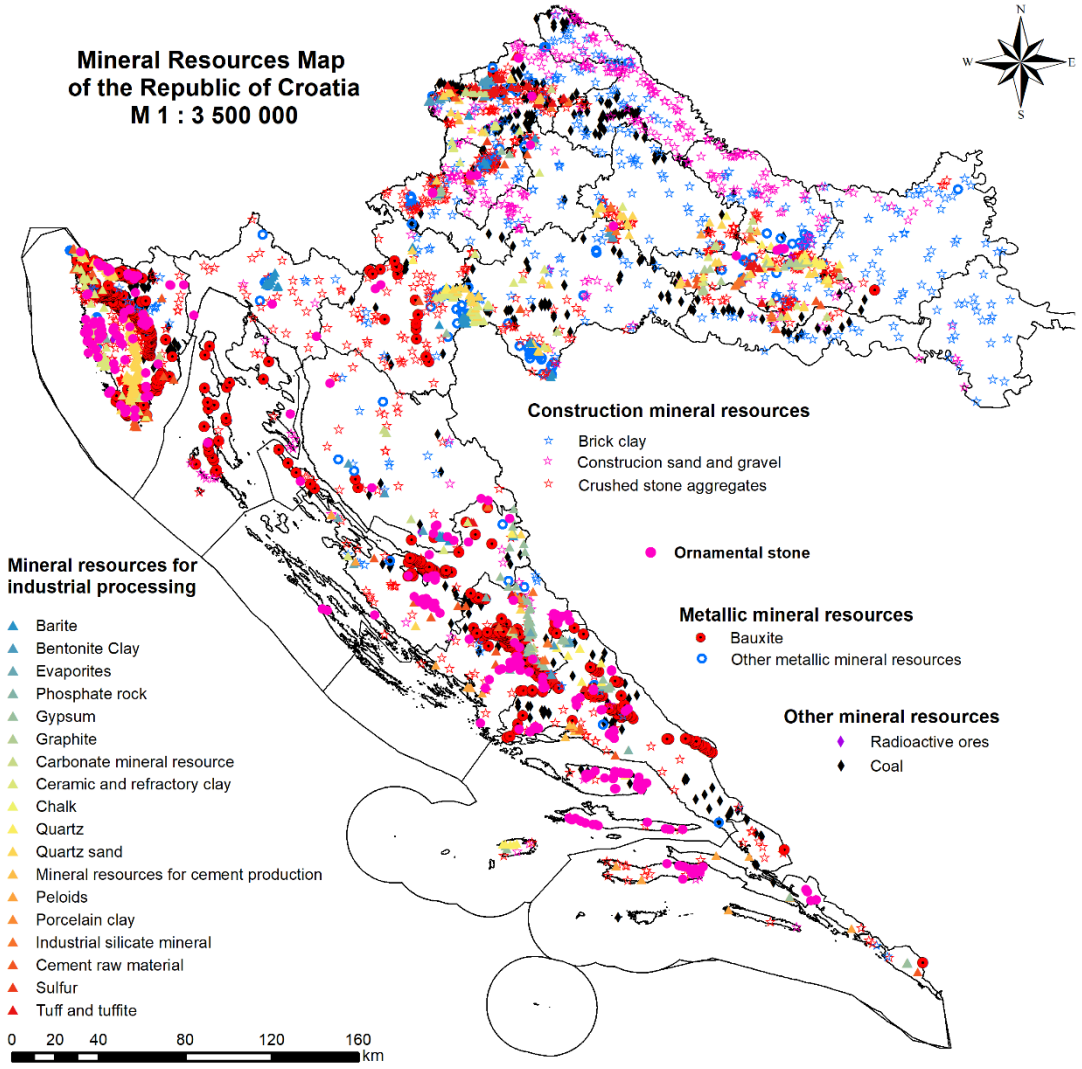

Figure 1. Mineral Resources Map of the Republic of Croatia showing the locations of deposits and occurrences of solid mineral raw materials (Source: Mineral Resources Database, Croatian Geological Survey).

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Acknowledgment

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High grade, polymetallic (Ag-Sb) mineralization of the Srebrenica Magmatic Complex, Bosnia and Herzegovina: A Critical Commodities Prospect at the Critical Time

DIM-ESEE Conference
15th – 17th October 2025, Dubrovnik, Croatia

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Presenting author: Aleksandar Mišković

Keywords: antimony, silver, epithermal, Bosnia, discovery

Abstract

Availability of critical metals on the European soil is essential for the continental strategic supply chain secirity and self-reliance in an increasingly unstable geopolitical environment. The Srebrenica Magmatic Complex (SMC) of eastern Bosnia and Herzegovina hosts Oligocene aged, epithermal Sb-Ag-Zn-Pb as well as auriferous skarn mineralizations within a Carbonfierous phyllitic basement and is a potential source of key commodities for the European markets (**Figure 1**) and as such offers a possibility to become one of Europe's own sources of key metallic resources.

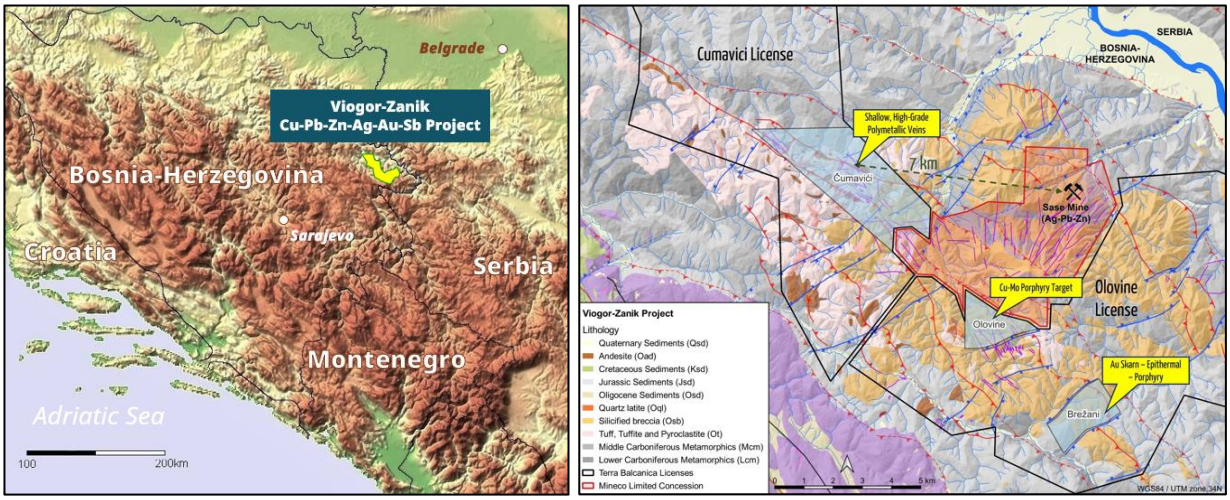

Figure 1. a) Regional disposition of the Terra Balcanica portfolio in Western Balkans; b) The geological map of the Viogor-Zanik project with the key polymetallic target zones along the NW-SE axis.

Terra Balcanica Resources Corp. has underataken detailed campaigns of propsecting and targeting the SMC (Viogor-Zanik Project) to identify mineral occuremces and advance our undersnading of the local ore body geomatry, composition, genesis, and ultimately, the size of minable resources. In doing so, Terra Balcanica has deployed a number of mapping,

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remote sensing, geochemical and geophysical techniques including the deployment of a dual airborne (TEM-magnetic) survey operated at 12.5 Hz to map the structural details up to 750 m depth. The airborne survey results have been evaluated together with geochemical soil sampling and structural analyses to define two principal targets of Brezani and Chumavichi which have been subsequently tested by up to 3.500 of exploratory drilling.

The dominant style of mineralization aloing the 7.2 km long, NW-SE Chumavichi corridors is shallow, high grade, fault-hosted, epithermal silver-antimony-zinc-lead-gold vein-hosted mineralization. The representative intercepts from the Chumavichi target are provided in **Table 1**.

Table 1. Highlights of the Chumavici target drill hole intercepts

Drillhole ID	Intercept (m)	Au (g/t)	Ag (g/t)	Zn (%)	Pb (%)	Sb (%)	Ag Eq. (g/t)
CMVD001	**4.0**	**0.84**	**131.5**	**4.59**	**2.12**	**1.85**	**1,138**
including	**2.0**	**1.62**	**261**	**9.10**	**4.20**	**3.70**	**2,264**
CMVD002	**2.0**	**0.23**	**144**	**8.26**	**4.27**	**0.44**	**693**
CMVD003	**8.7**	**0.81**	**105**	**1.17**	**0.70**	**1.20**	**710**
including	**2.0**	**1.16**	**289**	**3.16**	**2.03**	**3.50**	**1,936**
CMVD004	**11.0**	**0.30**	**225**	**0.83**	**0.56**	**1.48**	**882**
including	**1.7**	**0.81**	**1420**	**4.95**	**3.42**	**9.40**	**5,482**
CMVD005	**10.0**	**0.78**	**75**	**0.61**	**0.40**	**0.68**	**445**
including	**2.0**	**2.85**	**258**	**1.89**	**1.42**	**1.70**	**1,284**
CMV23004	**1.35**	**3.49**	**452**	**3.36**	**2.14**	**1.98**	**1,710**
CMV23001	**4.8**	**1.45**	**123**	**1.42**	**0.53**	**1.48**	**901**
CMV23001	**0.3**	**0.43**	**99**	**0.94**	**0.26**	**3.06**	**1,396**
CMV23002b	**3.8**	**0.63**	**116**	**5.20**	**2.56**	**0.46**	**574**
CMV23002b	**2.0**	**0.52**	**154**	**0.20**	**0.10**	**0.11**	**254**
CMV23003	**4.15**	**0.64**	**53**	**4.12**	**2.99**	**0.73**	**597**
CMV23004	**1.35**	**3.14**	**420**	**3.16**	**2.01**	**1.88**	**1,597**
CMV23007	**0.75**	**0.15**	**29**	**0.67**	**0.14**	**2.80**	**1,188**
CMV23009	**1.1**	**0.23**	**82**	**1.91**	**0.17**	**1.11**	**612**

On the other hand, Brezani is a multi-domain target that features a retrograde, chlorite overprinted Au skarn system with over 600 m of the surficial geochemical footprint underlain by a fault-hosted (intermediate sulphidation) epithermal antimony-silver zone of potentially world-class volume. The 2023 maiden drillhole intercepted 0.61 g/t AuEq over 88 m from surface with four additional drill hole assays to be released. Furthermore, a 1.2 km long conductor was intercepted at 480 m depth as Ag-Sb mineralized fault breccia surfacing to northeast. Drilling in 2023 yielded 436 g/t AgEq over 19.6 m including 746 g/t AgEq and 1.42 wt % Sb over 9.8 m. The underlying microdioritic porphyry emplaced at 550 m is interpreted as a heat engine and hydrothermal fluid source for the overlying Ag-Sb mineralization (**Figure 2**).

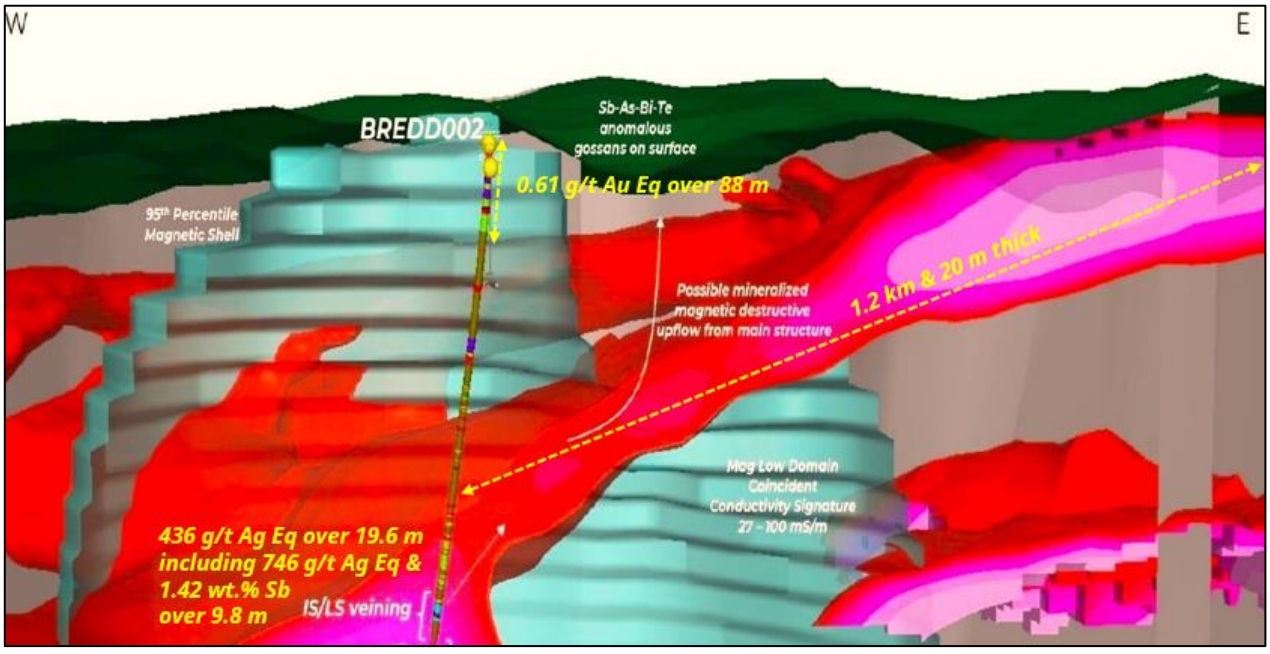

Figure 2. A subsurface conductivity profile at the Brezani target (27 mS/m < σ < *85* mS/m) showing a 1.2 km long, SW-dipping conductor interprted to be a reactivated reverse fault that served as a conduit for upwelling hydrothermal fluids.

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High-resolution field assaying and geochemical characterization of barite-rich drillcore intervals using portable XRF in the Rudabánya Ore district, northeastern Hungary: A calibration approach and applicability

DIM-ESEE Conference
15th – 17th October 2025, Dubrovnik, Croatia

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Oral	Poster	No preference
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Presenting author: Ferenc Mádai

Keywords: Barite, portable X-ray fluorescence spectroscopy (pXRF), drill core field assaying, Critical Raw Materials.

Abstract

Barite ($BaSO_4$) is a critical raw material essential to the energy, medical, and manufacturing sectors. However, its exploration is often limited by analytical challenges, particularly when it occurs in complex mineral systems with high iron content. Conventionally applied laboratory methods such as ICP-AES with a regular digestion procedure is ineffective when barite concentrations exceed 5 % to 10 % due to its extreme insolubility. Additional digestion procedure using a complicated fusion method increases further the analytical costs and time, affecting negatively on the financial efficiency and schedule of the exploration works. Classical gravimetric method is labour-intensive, required high operator skill, and were susceptible to interference from coexisting sulfates, sulfides, or other ions. Lab-XRF is a method can override the digestion problem, however is still relatively slow and costly for large sample numbers.

This study presents a field-adapted approach for the relatively rapid and reliable quantification of barium (Ba), iron (Fe), and other rock forming and target elements in drill cores using portable X-ray fluorescence (pXRF). A 25-meter interval of a drill core from the Rudabánya ore district in northeastern Hungary was tested for the applicability of this quantification method. The drillcore was analyzed using an Olympus Vanta™ pXRF device configured in dual-energy mode (HE+LE) to ensure comprehensive elemental coverage. More than 250 spot measurements were conducted, supported by a custom calibration workflow using pressed pellets prepared from the same core samples.

The Rudabánya mining district, located in northeastern Hungary within the Aggtelek-Rudabánya Mountains, holds considerable mineralogical and geochemical significance due to its intricate geological evolution and varied mineralization processes. Positioned within the tectonically active Darnó Zone – a strike-slip fault system linked to the Mid-Hungarian Lineament – the region's geological structure has been shaped by a succession of tectonic and ore-forming events. **(Bodor et al., 2013).**

The stratigraphic sequence of the Rudabánya region extends from the Triassic basement rocks to Neogene cover formations. The Triassic succession begins with the Bódvaszilas Sandstone Formation—a quartz-rich, well-sorted unit that hosts siderite and stratiform barite mineralization **(Földessy et al., 2009)**. This is overlain by the Szin Marl Formation, composed of laminated, organic-rich marls deposited under reducing conditions, serving as a key host for SEDEX-type Pb-Zn-barite mineralization **(Földessy et al., 2009**). Above these lie the Szinpetri and Steinalm Limestones, indicative of

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shallow marine carbonate environments, where dolomitization and metasomatic alteration led to the formation of sparry iron ores and hydrothermal veins **(Less et al., 2006)**. The Hallstatt Limestone, with its cherty, radiolarian-rich beds, reflects deeper hemipelagic marine conditions and is frequently associated with tectonic mélanges **(Velledits et al., 2011)**. Overlying these are Miocene to Quaternary deposits that constitute the post-orogenic sedimentary cover of the region.

Ore mining at Rudabánya started in the Medieval times, utilizing the native copper and galena-hosted silver of the oxidized, shallow-depth iron-rich horizons. The large-scale activity took place between 1872 and 1985 and used the shellow-depth limonitic ore and later the siderite-rich metasomatozed bodies. Barite appeas in the Rudabánya deposit in different forms associating to several stages, involving sedimentary deposition, metasomatic transformation, hydrothermal infusion, and supergene alteration processes. However, significant bodies of barite, up-to 2-5 meters thickness appear often at the border zones of the siderite blocks, usually together with increasing Cu sulphide mineralization. This barite type in Rudabánya has been the major target of mineral exploration in last years.

The main question in the present study was whether a reliable higher-resolution assay of barium can be obtained by the Olympus Vanta™ pXRF device. Direct assaying was not available because of the spectral overlap of the major peak of Ti ($K\alpha_1$) with the $L\alpha_1$ peak of Ba and calibration of the pXRF instrument was set up to identify Ti and not Ba. Laboratory XRF assays by a Rigaku Supermini XRF spectrometer were available for Ba from averaged samples of 1-3 metres sections of the borehole section. Along the 25 m drillcore section, 254 sampling points were measured in total. After each tenth measurements, a pellet from the previous laboratory XRF analysis series was used as internal standard.

Rather than relying solely on the device's internal algorithms, raw counts of spectral data (beamspectra) were used for the assaying and to generate regression curves calibrated against known concentrations from the laboratory XRF assays. Assay results from the 1-3 metres averaged samples and pellets of Ba standards were used for calibration (**Figure 1**). From the raw beamspectra, the area under the characteristic peak for the element was calculated and used. Method of the measurement is explained in **Figure 2**. This calibration significantly improved the quantification of Ba allowing identification of approximately three main high-grade barite zones where Ba concentrations exceed 55 wt %. These mineralized intervals, hosted in marl, ankerite-siderite, and siliciclastic rocks, are commonly alternate with elevated Fe-content. The results include the concentrations of Ba, as well as Fe, S, Cu, Ca, Sr, Mn, Si, and Al, their variation along the drill section.

The key novelty of this work lies in its custom spectral calibration and field-adapted spectral analysis strategy for Ba-rich systems. This transforms handheld XRF from a qualitative screening tool into a robust, quantitative method for barite exploration. The method enables decimeter-scale downhole mapping of Ba and Fe, offering far greater resolution than the previously obtained 1-3 m composites. It also facilitates rapid, in situ decision-making in polymetallic systems containing hard-to-digest minerals such as barite.

A further contribution is the evaluation of data reliability in zones with extremely high elemental concentrations. In two cases of the 254 completed measurements, calculated Ba values exceeded the theoretical maximum for pure barite (>58.8 % Ba). This anomaly demonstrates that physical properties such as absorbtion and fluorescence, grain size should be considered to refine the calibration. It was detected also that working temperature of the equipment affects on the result as well. By incorporating raw spectral data into the workflow, the method increases interpretive accuracy and improves detection of true mineralization patterns, even in complex ore systems.

Overall, this calibrated pXRF approach provides a rapid, non-destructive, and cost-effective alternative to conventional Ba assays. Its successful application in the Rudabánya district demonstrates its potential for broader use in CRM exploration, particularly in legacy mining regions where time, cost, and sustainability are major constraints.

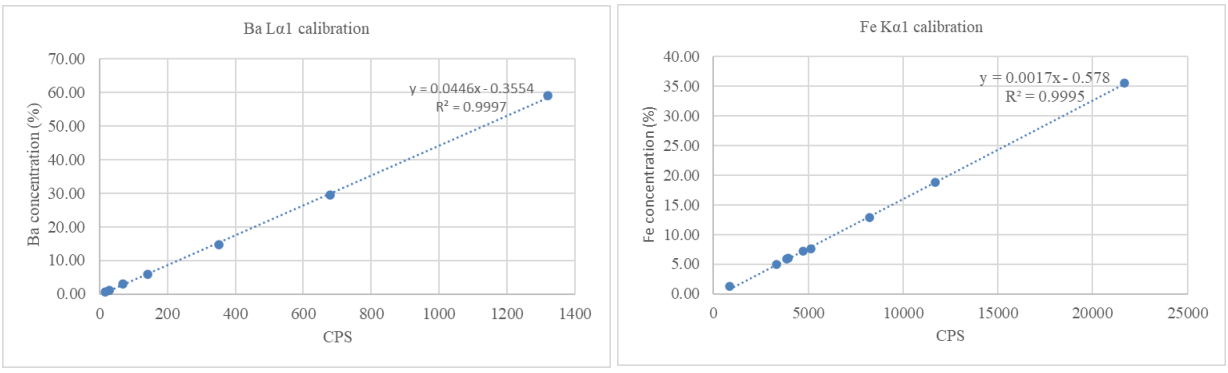

Figure 1. Calibration curves: developed from pXRF measurements and benchtop XRF measurements on the same standards.

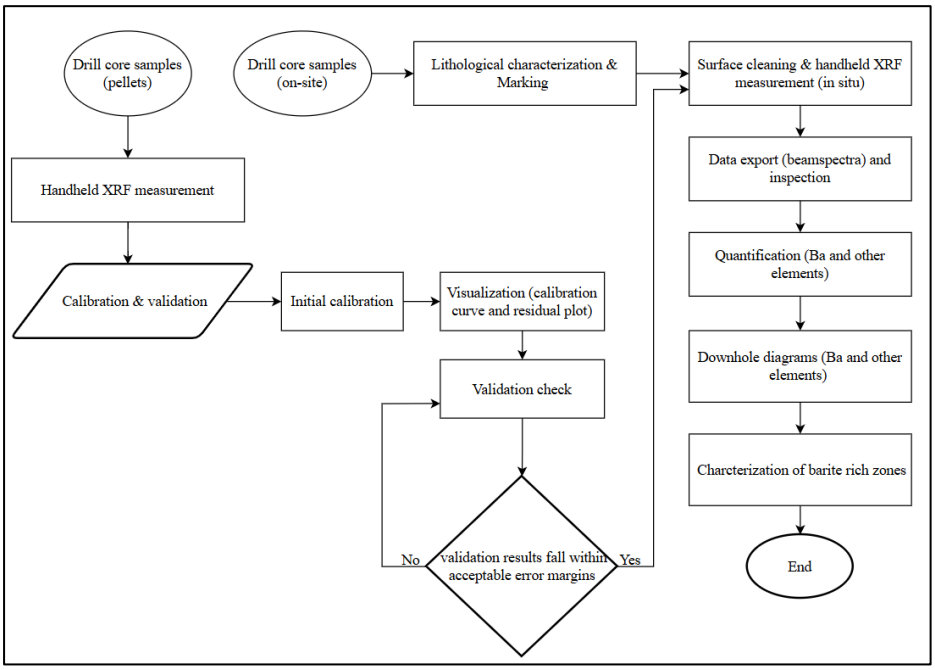

Figure 2. Methodological workflow of the pXRF measurements.

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Author's contribution

Gebreselassie G. Gebremedhin (MSc graduate): conceptualization, measurements, original draft and writing, **Ferenc Mádai** (associate professor): conceptualization, supervision, writing, review and editing

All authors have read and agreed to the published version of the abstract.

Towards Sustainable Deep Mineral Exploration: Insights from the MINOTAUR Project

DIM-ESEE Conference
15th – 17th October 2025, Dubrovnik, Croatia

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Presenting author: Magdalena Worsa-Kozak

Keywords: Deep Mineral Deposits, Sustainable Exploration, Innovation.

Abstract

Exploration drilling is often hindered by social acceptance, visual impacts resulting from the use of heavy machinery, and sometimes inefficiencies and high environmental costs. All of these factors make it challenging to discover new critical raw materials deposits needed for the transition of existing industries and for the development of modern high-tech industries. Traditional exploration methods can be slow and ineffective, leading to increased resource depletion and ecological disruption. As demand for these materials grows, finding innovative solutions that address the above challenges becomes a crucial step to move the raw material and transition agenda forward sustainably and effectively.

MINOTAUR is an EU-funded project that aims to develop a concept for Miniaturized Robotic Systems for Autonomous In-Situ Exploration of Critical Raw Materials in Deep Land Deposits.

MINOTAUR takes a fundamentally fresh look at exploration drilling and approaches it as a source-seeking and resourcing mapping problem, drawing inspiration from solutions in robotics, but where geology is a central part of the decision, with the outcomes of exploration enhanced through artificial intelligence and digital twin technology.

MINOTAUR aims to address the multiple challenges faced by exploration drilling experts by adopting a novel and revolutionary perspective, combining geological principles and concepts with modern technologies such as robotics, digital twin technology, and artificial intelligence. Along the way, MINOTAUR proposes novel research directions in allied areas like geophysics, sensing technologies in geology, environmental impact modeling of whole mineral and production systems, numerical modeling of entire mineral systems related to critical raw materials, new drilling techniques, high-resolution sensing technologies, and artificial intelligence with novel data processing tools for a robust and expeditious, prompt and qualitative geological assessment of the raw material deposit.

In the first year of the project, the eight partners involved are fully dedicated to developing the robot drilling concept and aligning with the expectations of two test sites (Portugal and Greece) for different mineral deposits. As the project evolves, multiple iterations will be necessary to fine-tune the laboratory proof of concept based on real-site input provided by industrial stakeholders.

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Lithium and Rare Earth Element Potential of Ion-Adsorption Clays in the Southern Tokaj Mountains, Hungary

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Presenting author: Ferenc Mádai

Keywords: ion-adsorption clays, lithium, rare earth elements, hydrothermal alteration, Tokaj Mountains.

Abstract

Ion-adsorption clays (IACs) are emerging as critical sources of rare earth elements (REEs) and lithium (Li), both essential for the European Union's clean energy transition and digital transformation (**International Energy Agency, 2024; European Commission, 2023; U.S. Geological Survey [USGS], 2023**). These deposits form through prolonged weathering of REE- and Li-enriched parent rocks, producing alumino-silicate minerals that adsorb valuable metal ions (**Benson et al., 2017; Sanematsu & Watanabe, 2016; Borst et al., 2020**). Given their strategic importance for renewable energy and high-tech industries, IACs are vital for Europe's economic resilience (**European Raw Materials Alliance [ERMA], 2021**).

This study investigates the mineralogy and geochemistry of hydrothermally altered acidic volcanic rocks in the Southern Tokaj Mountains, Hungary, to evaluate their lithium (Li) and rare earth element (REE) enrichment potential. Geochemical patterns of these deposits are compared with globally known significant Li-rich clay systems.

The Tokaj Mountains are part of the Inner Carpathian Arc and originated within a calc-alkaline volcanic island arc system characterized by predominant andesitic, dacitic, and rhyolitic magmatism (**Zelenka et al., 2012**). Radiometric K/Ar dating indicates that volcanic activity – particularly andesitic and rhyolitic – was most intense during the Miocene to Pliocene period (approximately 15 million years ago to 9 million years ago), coinciding with extensional tectonic processes in the Pannonian Basin (**Pécskay & Molnár, 2002**).

The Tokaj Mountains display a distinctive geochemical enrichment pattern, primarily resulting from the hydrothermal alteration of rhyolites and rhyolitic tuffs. This process has led to elevated concentrations of lithium (Li), thorium (Th), uranium (U), and rare earth elements (REEs), largely driven by potassium metasomatism and the influence of silica-rich hydrothermal fluids (**Zelenka et al., 2012**). Deeply eroded zones in nothern part of the Tokaj Mountains, such as Rudabányácska, Telkibánya are characterized by adularia-sericite alteration, whereas shallower acid-sulfate, steam-heated alteration systems associated with the Sarmatian-Pannonian stage prevail near Mád and the Szerencs Hills (Fig. 1.). Additionally, well-preserved distal hydrothermal environments are found in lacustrine siliceous and clay-rich deposits around Mád, Regéc, and nearby localities (**Pécskay & Molnár, 2002**). Post-volcanic hydrothermal activity in the region has been dated to between 12.1 and 10.4 million years ago.

Geological and mineralogical investigations of the Southern Tokaj Mountains, Hungary, reveal a setting analogous to major Li-clay deposits, such as the Naomugeng deposit (China) and the McDermitt Caldera (USA) (**Li, 2021; Benson et al., 2023**). XRD analysis indicates a mineral assemblage dominated by alumino-silicates – primarily alkali feldspar, quartz, muscovite, illite, kaolinite, and zeolite – where hydrothermal alteration plays a critical role in the enrichment potential of lithium and rare earth elements within the clay matrix (**Figure 1, Figure 2, Figure 3, Figure 4**). Samples

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from Bodrogkeresztúr quarry exhibit orthoclase, albite, and illite, supported by elevated K, Th, and U concentrations. Stratigraphic variations in Mád III. quarry highlight differing alteration intensities: the lower horizon contains orthoclase and quartz, while the upper horizon shows advanced alteration (smectite, illite, dickite), linked to K depletion and Th enrichment. Rátka quarries feature zeolitized tuffs (heulandite, clinoptilolite), indicating multi-phase alteration.

Whole-rock geochemistry (XRF) classifies the rocks as peraluminous and calc-alkaline, with trace elements (Th, Ce) moderately correlated. Lithium concentrations (20 ppm – 79 ppm, ICP-MS) peak in sericite-chlorite zones, with normalized Li anomalies revealing spatial variability. REE patterns show LREE enrichment and negative Eu anomalies, consistent with feldspar fractionation and hydrothermal processes. Elevated Li correlates with argillic alteration (chlorite, illite), reinforcing hydrothermal control on enrichment (**Figure 3** and **Figure 4**).

These findings position the Southern Tokaj Mountains as a possible Li-REE exploration target, with mineralogical and geochemical parallels to global clay-type Li deposits.

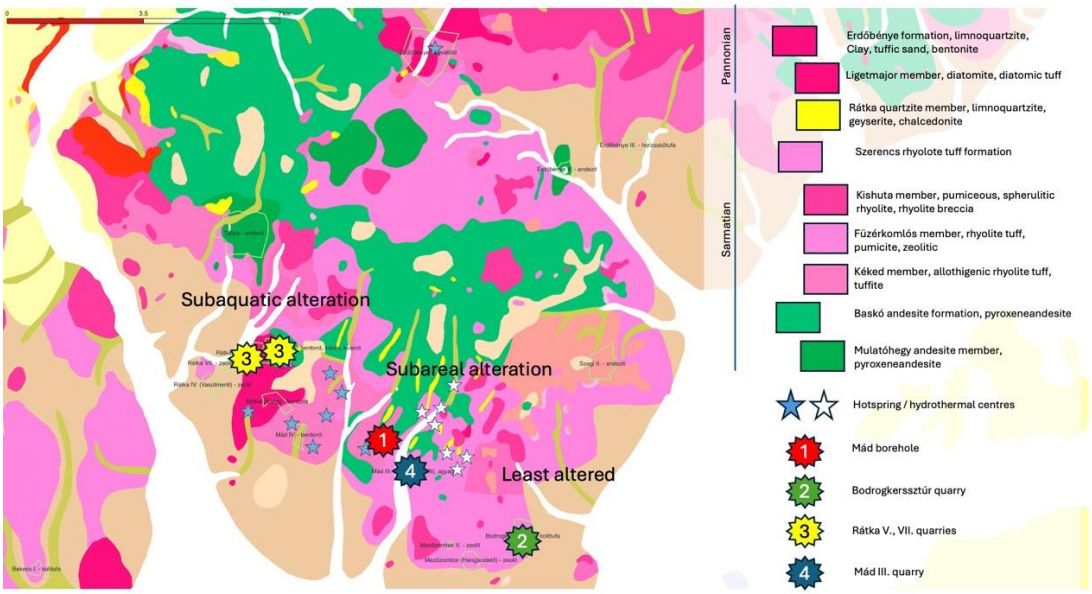

Figure 1. Geological map of the area with hydrothermal centres and sources of samples. (sources: MBFSZ map server, Mátyás, 1974).

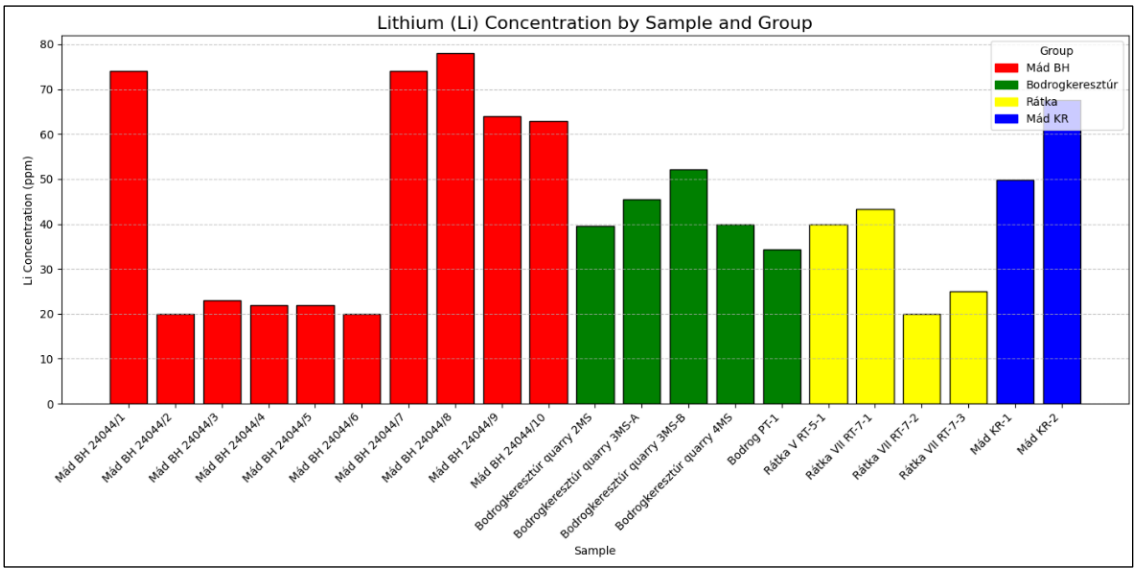

Figure 2. Lithium concentration in the study area determined by ICP-MS analysis.

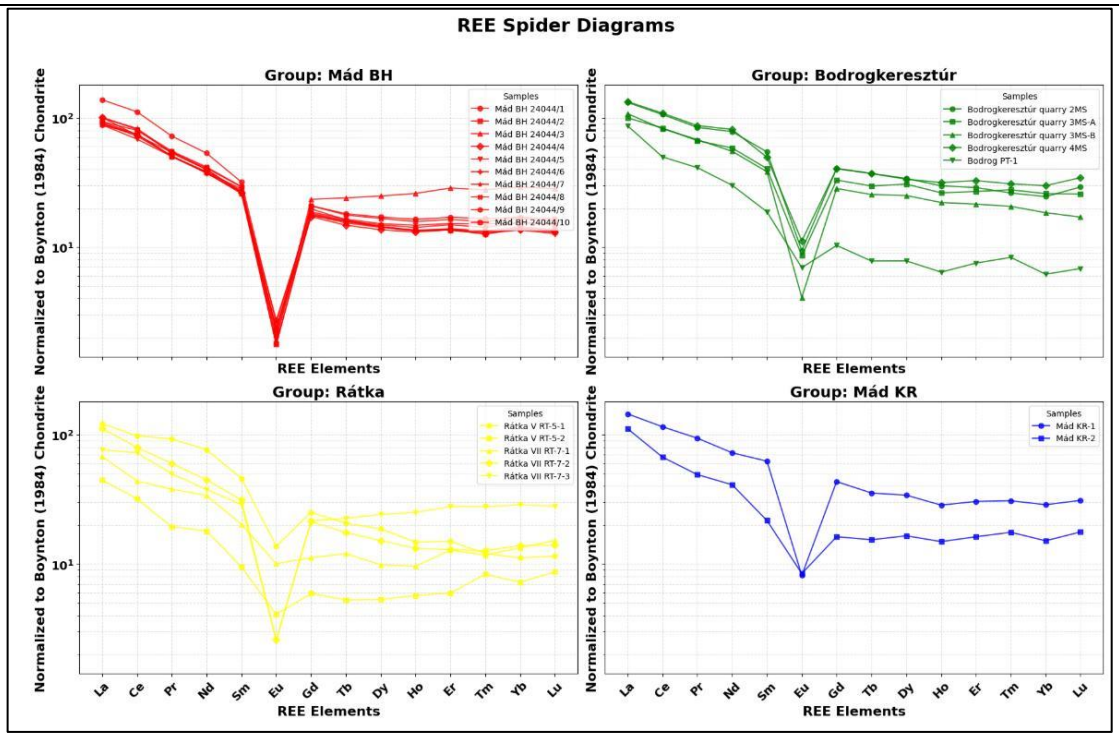

Figure 3. REE concentration in the study area determined by ICP-MS analysis.

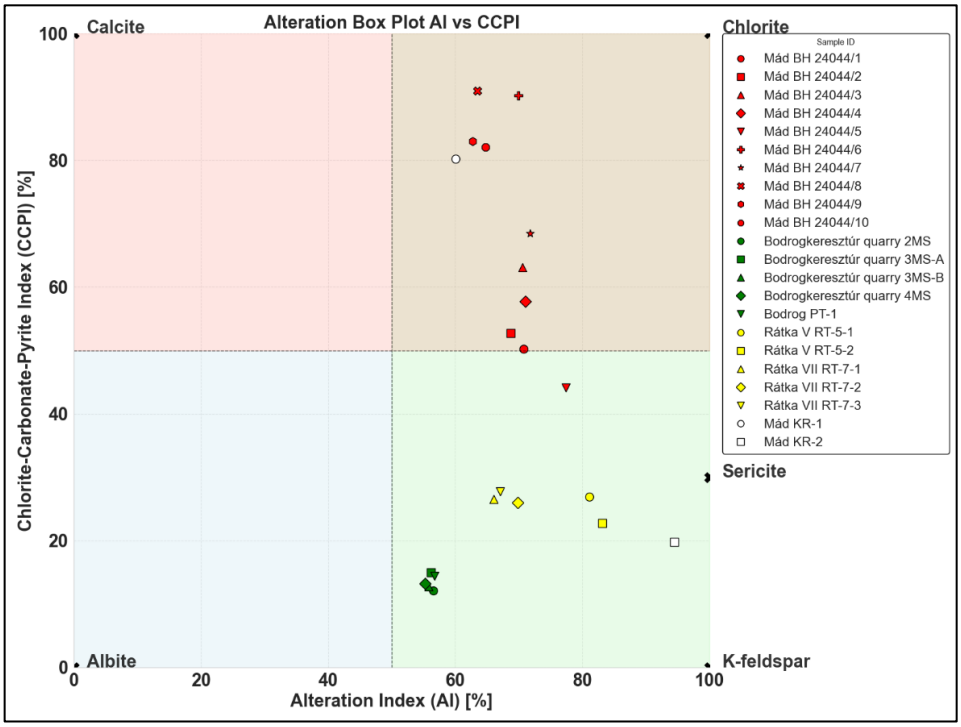

Figure 4. Alteration boxplot shows the advancement of alteration from K-feldspar to sericite to advance chlorite alteration.

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Author's contribution

Abaker Almoufty Mohamed (MSc student): conceptualization, investigation, original draft and writing. **Mádai Ferenc** (associate professor): conceptualization, supervision, review and editing.

All authors have read and agreed to the published version of the abstract.

Information Technologies in the Formation of a Comprehensive Assessment of Synergistic Effects of Environmental Problems of a Modern City

DIM-ESEE Conference
15th – 17th October 2025, Dubrovnik, Croatia

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Please mark in what field is your Abstract (mark with "x" your selection):

Field	
Raw materials prospection and discoveries	x
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Raw materials education	

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Mark your preferred presentation mode:

Oral	Poster	No preference
	x	

Presenting author: Nazariy Popadynets

Keywords: Environmental monitoring, carbon-neutral economy, urbanization, waste, energy generation, transport, synergistic impact, integrated environmental assessment.

Abstract

To study the elements of the integrated ecological space of a modern city, we will consider it as a closed space from the standpoint of administrative and territorial structure, spatial planning on the geographical surface of the earth, management and property. The boundaries of territorial communities, including their centres, cities, towns, and villages, form a complex closed system with a corresponding number of elements that interact and integrate with each other in the process of functioning and development of the territorial community. Complex systems are those in which the functioning of the elements is so interdependent and interrelated that their separate study is simply impossible or will lead to incorrect conclusions **(Vovk, Drohomyretska, 2002)**. It is the environmental components of a complex system of a territorial community that require an integrated and systematic approach, as they are naturally interconnected and often move beyond the will of a person.

According to studies and statements by some scientists, a new natural unit can be used for a territorial community and individual settlements, which closely intertwines the natural environment, combined socio-economic, demographic, technical, political and other blocks. The geosociosystem was adopted as such a unit as a geographically delimited system that functionally combines ecological, social and economic blocks, where all environmental, socio-economic, demographic, information and other processes organised and implemented by people take place **(Golubets et al. 2007)**.

As is known, the relationship, interconnections and integration of the potentials of objects and subjects that occur in a closed system between its elements form a corresponding synergistic effect, which is a carrier of both sustainable development and a carrier of deterrence or negative impact **(Prokopenko, Petrushenko, 2013)**.

The ecosystem of a modern city is formed under the influence of and on the basis of a number of components of activities and functioning of entities located on its territory, which can be divided into separate areas that interpenetrate, i.e. integrate, intertwining negative and positive synergistic effects. An important task here is to effectively weigh the advantages and disadvantages of mutual synergies, in particular in closed city systems and their extension to open spaces: geographical (environmental), market, demographic, and others. Let us consider the following areas of city life, in which

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the manifestations of synergistic influence and interconnections between them are most concentrated in the ecological space of the modern city (**Figure 1**).

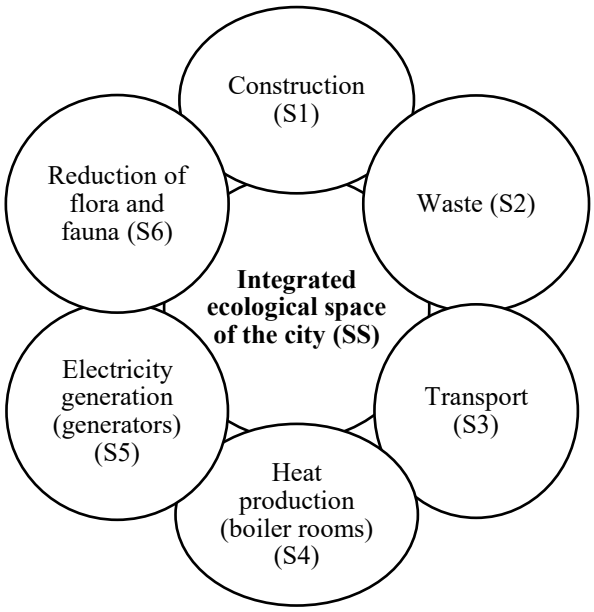

Figure 1. Synergy of environmental problems of a modern city.

Construction. (S1) The construction of housing facilities, various types of infrastructure for living and use by city residents, conducting economic activities, obtaining other services necessary for life, health, development, etc. can be attributed to the key areas that ensure the existence of the city in principle. For example, consider the trend of housing commissioning in the Lviv region, the vast majority of which is built in the city of Lviv. According to the regional statistics department, 1015.7 thousand square metres of housing were commissioned in 2020, 1211.5 thousand square metres in 2021, 720.6 thousand square metres in 2022, 769.5 thousand square metres in 2023, and 1062.4 thousand square metres in 2024, which is 32 % more than in the previous year **(Main Department of Statistics in Lviv Oblast, 2025)**.

Waste. (S2) The growth of housing construction directly leads to an increase in the city's population, improvement of the demographic situation, which extends the impact of positive synergy through increased employment of residents, improvement of their standard of living and quality of life. At the same time, there is a negative synergy in the environmental space due to the increase in natural human waste, solid household waste, technological waste, etc.

Transport (S3) In parallel with the increase in the city's population, its welfare, income, development, comfort needs, and satisfaction of mobility, the number of motor vehicles on city streets, parking in yards, and adjacent territories is also growing. This process can be partly attributed to the positive synergistic impact on the socio-economic component of human life quality.

Heat production. (S4) Heat supply to the residential sector of the city and non-residential industrial and commercial premises from existing heat facilities (boiler houses), both gas and solid fuel technologies, remains the most common. The emission of harmful substances into the atmosphere as a result of fuel combustion requires the installation of equipment and efficient technological processes to capture and clean these emissions. As a rule, heat and power companies do not operate without the presence of treatment facilities. Nevertheless, one of the tasks of monitoring the purity of emissions, the completeness of treatment, and separately the quality result due to long-term use of equipment, outdated technologies, etc.

Alternative sources of electricity.(S5) The full-scale invasion of Ukraine by Russian troops, destruction of energy infrastructure at various levels of generation and transmission resulted in electricity shortages and forced power outages for consumers. The negative synergies have had a particularly significant impact on the functioning of businesses, which have partially shut down their operations or are forced to install separate local generation units (electric generators) running on diesel fuel.

Flora and fauna. (S6) The potential of flora and fauna of modern cities is mainly represented and formed in parks, squares, vacant land plots, lawns, etc. A characteristic feature of a modern city in Ukraine is the struggle of residents and the public to preserve parks and green spaces, create new green areas, places where birds and small fauna can nest. Assessment of the environmental impact caused by the reduction of natural resources of green spaces, grass cover and the consequences of this process in modern cities should be carried out along with other areas, as it is inevitably integrated into the ecological space.

The enhanced, enriched synergy of environmental problems (EP) of the modern city requires new scientific research, the use of the latest technologies to establish indicators of impact on health and life of the population, and a comprehensive and systematic approach to establishing links and aspects of integrated impact. With the help of advanced IT technologies, mechanisms, methods, tools, and programmes for comprehensive environmental assessment should be found, and on its

basis, ways to address and balance the positive and negative impacts of human activity on the environment should be proposed.

For a comprehensive assessment of the environmental problems of a modern city, it is necessary to take into account the impact of all the above environmental parameters on the environmental safety of the city and to form a generalised quantitative value of the synergy of environmental problems. Such a value will depend on many parameters of influence, which are determined by location, time of day, weather conditions, the presence of various neighbouring objects of influence, biodiversity and other means **(Gomeniuk, 2024).**

The generalised value of the indicator can be calculated by taking into account the probability of occurrence of extremely dangerous values of parameters (denoted by pi), which will characterise the impact on climate change, the presence of landfills, additional energy costs for the construction industry, the presence of human waste, solid household waste and technological waste with an increase in the number of people in the city, harmful emissions into the atmosphere through transport, especially in places of the largest concentration of vehicles, traffic jams, emissions of harmful.

All of the above indicators can be characterised by parameters (denoted by Infi) that will determine their impact on the environmental safety of the city from the least dangerous value (the impact of harmful pollution on public health for the obtained numerical values is absent or insignificant) to the most dangerous (the impact of pollution is determined by critical values on the maximum permissible scale and has a negative impact on human health). We set the values of the impact of the indicators by numbers in the range from 1 to 5, which will correspond to the values "very weak", "weak", "medium", "significant" and "very significant". It is clear that each of the values will be determined by a set of numerical values, each of which is determined by standards for the level of pollution.

The general indicator of a comprehensive assessment of the environmental problems of a modern city is

$$SS = \sum_{i=1}^{6} S_i * Inf_i * p_i$$

where *Si*= {0, 1} is a coefficient that determines the presence of "1" or absence of "0" for a particular synergistic indicator (construction, waste, transport, heat production, alternative energy sources, flora and fauna) to calculate the environmental situation in the city depending on the selected part of the city territory.

The maximum value of the indicator for a comprehensive assessment of the city's environmental problems can be 30, which will be determined by the maximum impact of all six synergistic indicators on the environmental situation.

For a comprehensive assessment of the city's environmental safety, web or mobile applications can be used, which will use optimisation mathematical models to predict the threats of negative impact of pollutants on public health. As an example, such information research of hazardous situations can be carried out using fuzzy logic algorithms.

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Author's contribution

Nazariy Popadynets (senior researcher): scientific supervision, methodology design, conceptualization, supervising the scientific and technical aspects. **Hanna Oleksyuk** (associate professor): critical review, funding acquisition, English language support. **Andriy Lahun** (associate professor): data curation & preprocessing. **Jacek Obrzud** (associate professor): model development and testing. **Oleksandr Pravdyvets** (associate professor): formal analysis, validating results.

All authors have read and agreed to the published version of the abstract.

Slovenian national exploration programme of critical raw materials and their carriers

DIM-ESEE Conference
15th – 17th October 2025, Dubrovnik, Croatia

Gorazd Žibret[1*]
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Field	
Raw materials prospection and discoveries	x
Mining methods	
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Presenting author: Gorazd Žibret

Keywords: CRM act, geochemistry, geophysics, geological mapping.

Abstract

There is very limited information available regarding the potential of critical raw materials (hereinafter: CRM) in Slovenia. Over the past 45 years, systematic research has not utilised modern analytical methods or incorporated the latest findings on the genesis of ore deposits. In addition, past systematic research of ore deposits during the Yugoslavia era focused only on base metals, not on commodities that are critical today. After the end of 80's the exploration activities on the territory of Slovenia almost ceased to exist. Therefore existing knowledge on metallic raw materials does not meets the needs of the present, while ore genesis interpretation was made by using outdated geochemical and geological knowledge. To assess the situation regarding the CRM potential in Slovenia, it is essential to:

- collect remote sensing data and conduct research to identify the presence of previously unknown ore bodies at depth,
- collect data from the surface using modern analytical methods, with a focus on critical raw materials, and by using modern geological knowledge.

It has been recognised, that Slovenia has favourable geological conditions for the discovery of various CRMs, including bauxite, antimony, baryte, copper, germanium, bizmuth, manganese, lithium and others **(Žibret, 2012; Pučko, 2021)**. The list was prepared by assessing various known occurrences of metallic ores in Slovenia, as well as existing geological knowledge, obtained in the last decades.

Considering the fact that the EU economy has been extremely dependant on the imports of various raw materials, and that the latter has become a mean for a polytical pressure, the EU decided to obtain various measures to reduce its dependency on the imports of raw materials. One of the measures is to stimulate the domestic production. This was established by the regulation (EU) 2024/1252 of the European Parliament and of the Council, dated 11 April 2024, that set a framework to ensure a secure and sustainable supply of CRM (hereinafter: CRM Act). In Article 19 CRM Act obliges EU Member States to prepare a National Exploration Programme for Critical Mineral Raw Materials and Their Carriers (hereinafter: NEP). As a direct consequence of this act the Ministry of Natural Resources and Spatial Planning has assigned the Geological Survey of Slovenia (GeoZS) to prepare a draft of the NEP and its technical basis at the second half of the year 2024. A group of experts from various fields of geology within GeoZS has been established and immediately started working. Firstly it was needed to assess current geological data and knowledge, followed by the assessing CRM potentials, identification of geological formations which are potential carriers of CRMs, areas of metallic mineral occurrences, gaps in data and other parameters. The group also proposed the objectives and the scope of the Slovenian NEP.

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In January 2025 the working group organised the first public consultations, where findings of the first steps were presented to the interested public. After consultations, the group prepared the so called "action plan". It contains 2 important parts: data collecting methods and "auxiliary tasks". Data collecting methods includes:

1) Remote sensing methods:

- aeromagnetometry: passive measurements of the magnetic field, which can be used to identify hydrothermal structures down to a depth of 1000 m, and for direct determination of Fe reduction limits in depth, which is an indirect indicator of geological changes;
- gamma spectroscopy: airborne radiometric measurements of K, U, and Th radiation, to identify geological structures and the occurrences of certain types of ores (e.g. porphyry Cu-Au-Mo ores, granitoid ores Sn, W, Mo, U, REE) and pegmatites (Li, REE);
- airborne electromagnetic measurements (TDEM): active measurements of the electromagnetic field from the air, which can be used to determine the distribution of electrical resistivity of rocks down to a depth of approximately 500 m, which will allow identifying of various mineralizations with metals, as well as tectonic and geological structures, the presence of aquifers, and the determination of weathering depths;
- gravimetry: precise measurements of the gravity field, with the aim of identifying occurrences of larger intrusions at depth, which may be the source of mineral deposits, and to determine deeper geological structures, especially the contacts between lineaments, which are often mineralised.

2) Geochemical research: analyses of stream sediments, lithogeochemical and hydrogeochemical research, supplemented with mineral composition and determination of CRM carriers.

3) Geological mapping: field geological surveys, laboratory and office work, which includes determining the mineralogical structure, microscopy in reflected and transmitted light, electron microscopy, paleontological and other laboratory analyses that are not included in the scope of geochemical research, map drawing, and the production of 3D models.

4) Field geophysical research: reflection seismicity, which is an active field geophysical method that can determine deep structures in Tertiary and Quaternary basins and provides data on deep geological structures and active tectonics.

Auxiliary tasks, which are needed for the successfull implementation of NEP, includes tasks like NEP governance, control and evaluation, stakeholder and public engagement, data handling and storage and metallogenic interpretation. Action plan also defined exploration areas and exploration methods for the specific areas, risks, environmental impacts and potential uses of collected data for other applications, like planning for underground storage of CO_2 and other gasses, better assessing seismic and other geological hazards, exploitation of other raw materials and geothermal energy and many others.

The proposed exploration areas (**Figure 1**), data collecting methods (**Table 1**) and auxiliary methods were presented on the second public consultation event, which occurred in April 2025. The general outline of NEP was also presented to the public in various newspaper articles and to the experts in expert events. The final document **(Žibret et al., 2025)** was prepared in May 2025 and submitted to the government. The government then requested shorter, condensed version of the document, which was prepared according to their instructions, which served as the Slovenian NEP. The document was adopted by the Slovenian government in July 2025 and submitted to Brussels for the evaluation by the EU Commission.

It needed to be noted, that Slovenian NEP is a modular and dynamic document, decission about timeline of its implementation will be done according to the available funds, results of the previous tasks (assessing new probability of occurrences), accessibility, economics of possible future exploitation, impacts on the environment and society and other relevant parameters.

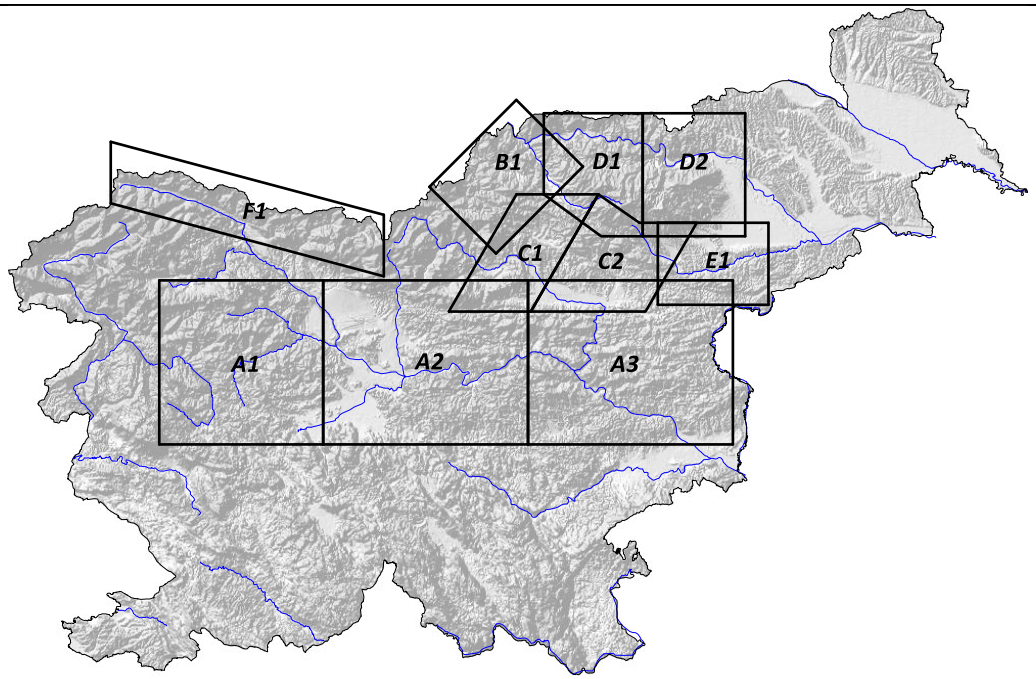

Figure 1. Proposed exploration areas.

Table 1. Proposed data collecting methods.

AREA	CABINET WORK - data analysis and literature review	AERIAL GEOPHYSICAL RESEARCH (remote sensing)	GEOCHEMICAL RESEARCH	GEOLOGICAL MAPPING	FIELD GEOPHYSICAL RESEARCH
A1+A2+A3	x	x	x	x	x
B1	x	x	x	x	x
C1+C2	x	x	x	x	x
D1+D2	x	x	x	x	x
E1	x	x	x	x	
F1	x		x	x	

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Advancing Europe's Critical Raw Materials Supply: Results of the Horizon Europe AGEMERA Project

DIM-ESEE Conference
15th – 17th October 2025, Dubrovnik, Croatia

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Please mark in what field is your Abstract (mark with "x" your selection):

Field	
Raw materials prospection and discoveries	x
Mining methods	
Geometallurgy and sustainable extraction	
Materials recycling and waste management	
Raw materials education	

Please mark do you plan to submit a full paper manuscript (mark with "x" your selection):

YES	NO
	x

Mark your preferred presentation mode:

Oral	Poster	No preference
x		

Presenting author: Josipa Kapuralić

Keywords: Critical Raw Materials (CRMs), Mineral Exploration, Geological Modelling; Non-Invasive Geophysical Methods, Data Integration Platform.

Abstract

The Horizon Europe project AGEMERA (Agile Exploration and Geo-modelling for European Critical Raw materials) has advanced the exploration of critical raw materials (CRMs) in Europe and in partner regions using innovative, non-invasive geophysical methods. AGEMERA is funded by the Horizon Europe program and is in line with the European Critical Raw Materials Act, which aims to ensure a sustainable and autonomous supply of CRMs essential for the EU's green and digital transformation. The project developed and applied innovative, environmentally and socially responsible exploration methods, which were demonstrated on an area of around 4700 km² in European countries (Finland, Bosnia and Herzegovina, Spain, Bulgaria, Poland) and in Zambia. The consortium consists of 20 partners from 11 countries, including universities, research institutions and the mineral exploration industry. The aim of the consortium was to identify new areas for resource exploration and develop environmentally friendly methods and tools to source them; a systematic assessment of societal perceptions, including expectations and fears, regarding mineral exploration and mining through representative surveys among citizens in the project countries; to raise awareness of the green and digital transition and the importance of CRMs in daily life; to promote the UNFC and UNRMS by training future experts. Technical innovations within the project included passive seismic methods, which have shown significant potential for imaging underground structures in difficult mining environments, drone surveys combining electromagnetic, magnetic and radiometric sensors for rapid aerial exploration, and muon imaging (or muography) – a technique borrowed from astroparticle physics that uses naturally occurring cosmic-ray muons to image density contrasts in underground structures. The integration of passive seismic imaging with geological and borehole data provided valuable insights into the subsurface architecture at the Mina Concepción site (Spain). The results show that applied passive seismic methods can contribute to structural mapping and support traditional exploration methods. The development of an integrated drone-based surveying system is advancing the field of drone-based geophysical surveying. Compared to traditional airborne and ground-based methods, this system is cheaper, faster, safer and multi-method, with particular innovations in the miniaturization of instruments and the development of a fully airborne EM method. The exploration of the Posušje site (Bosnia and Herzegovina) has shown that the resolution of drone data is much coarser than that of ground geophysical surveys. Therefore, drone surveys should be used to map larger areas and identify areas on which ground investigations can be focused. Muon tomography provides exceptional resolution and enables detailed 2D to 4D imaging of rock and ore body densities, significantly improving the accuracy of genetic models of mineral systems. At the Jajce site (Bosnia and Herzegovina), muon tomography has successfully imaged a bauxite lens with a density contrast of ~0.3 g/cm³ – 0.4 g/cm³ at a depth of ~50 m in a structurally complex karst environment where ground geophysical methods had difficulty resolving the target. The

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method is best suited for targets at medium to great depth (>100 m), especially where seismic, ERT or EM methods are limited by surface conditions, noise or weak contrasts in physical properties. Integration with ground geophysical data (ERT) improved the model and reduced inversion ambiguity. Therefore, the logical outcome of applying innovative methods was to propose a new protocol for ground geophysical surveys in combination with newly applied methods for CRM exploration.

The results of the applied exploration methods were integrated into a web-based graphical user interface (GUI) – a cloud-hosted platform that provides 2D/3D visualization, interactive tools and even a natural language processing AI engine based on large language models (NLP LLM) that simplifies navigation through the extensive data and ensures that users can easily find the information they need, allowing both experts and non-experts to intuitively explore geospatial datasets. These complementary methods generate rich subsurface datasets in diverse geologic contexts ranging from hard rock ore deposits to secondary resource sites. The improvement and development of new mineral system models focused on the following CRM-bearing ore deposit types: karst bauxite from Bosnia and Herzegovina, porphyry copper deposits (e.g. PGMs) in Bulgaria, including epithermal gold systems with potential CRM enrichments, high tonnage porphyry-type W-Au deposits in central Iberia, mafic potential Ni-Cu-Co deposits in the Iberian pyrite belt.

Beyond the geotechnical field, AGEMERA dealt with the socio-economic dimensions of the exploration of critical raw materials. Surveys are conducted in local communities to determine perceptions and wishes in relation to mining and exploration, with anonymized data fed into the open access platform. The project also produced educational materials, serious game and awareness-raising campaigns that reached a wide audience and increased public understanding of CRMs. A SoftGIS mapping approach enabled the integration of social, cultural, environmental and economic considerations with geological data and supported strategies that aligned resource potential with social acceptability.

This project has shown that Europe can combine cutting-edge geophysical techniques, AI-powered data platforms and industry engagement to support sustainable access to key raw materials. The project has contributed to Europe's strategic autonomy and sustainable raw materials policy by demonstrating non-invasive exploration and incorporating societal perspectives.

Acknowledgment

Acknowledgements are extended to all contributors involved in the AGEMERA project.

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Author's contribution

Josipa Kapuralić (assistant professor): conceptualization, writing – original draft preparation and editing, **Franjo Šumanovac** (professor): review and editing.

All authors have read and agreed to the published version of the abstract.

Rockfall Mitigation Measures in Open Pit Mines: Case Study of Mandai Quarry

DIM-ESEE Conference
15th – 17th October 2025, Dubrovnik, Croatia

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Presenting author: Marko Boričević

Keywords: rockfall protection, slope stabilisation, protective measures, shallow landslides, mudflows

Abstract

Open pit mining operations often face the challenge of rockfall hazards, especially on steep slopes or areas with poor geological stability. This abstract summarizes a case study conducted at Mandai Quarry in Singapore, focusing on modern rockfall mitigation techniques utilizing flexible protection systems.

The study highlights the limitations of traditional stabilization in certain quarry sections and emphasizes the importance of advanced rockfall barrier systems and meshes. These systems, made from high-tensile steel and designed to withstand energies up to 12,500 kJ and tensile strengths up to 360 kN/m, are validated by European standards (ETA, CE) and offer effective protection against rockfalls and shallow landslides (see **Figure 1**).

Figure 1. High tensile steel solutions for natural hazard mitigation (meshes and barriers).

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The Mandai Quarry project combined the use of catch fences (barriers), slope stabilization using TECCO® mesh, and rock nailing, with site-specific geotechnical analysis guiding the implementation. Design tools such as RAMMS and Rockfall by Dr. Spang were used for simulation and system dimensioning, such as trajectory and energy modeling. These simulations accounted for slope geometry, block characteristics, and surface roughness to optimize barrier placement and height. As far as slope stabilisation is considered, RUVOLUM® program was used to determine nail distance and nail type based on input data such as friction angle, cohesion, density of material and slope angle.

Rockfall barriers and slope stabilisation meshes were strategically placed based on simulation data and geological assessments to intercept high-risk zones, ensuring the safety of access roads and operational areas. **Table 1** contains a summary of rockfall simulation results for the main cross sections that were defined and tested, and Table 2 contains a summary of input parameters and results for slope stabilisation measures.

Table 1. Summary rockfall results for main cross sections.

Cross section	CH375	CH620	CH670	CH775	CH1050
Weight design boulder	11.3 t	11.3 t	11.3 t	11.3 t	11.3 t
Max. impact energy	226 kJ	354 kJ	737 kJ	317 kJ	234 kJ
Min. impact energy	0 kJ	41 kJ	21 kJ	21 kJ	9 kJ
Probability of impact	81 %	58 %	74 %	82 %	61 %
Barrier type	GBE®/RXE®/ROCCO®				
Energy class	250 kJ	500 kJ	1500 kJ	500 kJ	250 kJ
Total lenght	290 m	60 m	110 m	100 m	350 m
Barrier height	2 m	3 m	4 m	3 m	2 m

Table 2. Summary of input parameters and results for slope stabilisation.

Rock type	Friction angle [°]	Cohesion [kN/m^2]	Density [kN/m^3]	Slope [°]	Nail distance [m]	Nail type
Loose rock (t=0.75 m)	56,3	0,0	27,0	75	3,20	GEWI 32
	56,3	0,0	27,0	80	2,95	GEWI 32
	56,3	0,0	27,0	85	2,75	GEWI 32
Loose material	56,3	0,0	27,0	55	3,05	GEWI 32
	56,3	0,0	27,0	60	2,85	GEWI 32
Intact rock (t=0.5 m)	59,0	2,0	27,0	80	3,50	GEWI 32
	59,0	2,0	27,0	85	3,20	GEWI 32
	59,0	2,0	27,0	90	2,95	GEWI 32
Shear zone (t=0.75 m)	56,3	0,0	27,0	80	2,95	GEWI 32
	56,3	0,0	27,0	85	2,75	GEWI 32

In **Table 2**, the cohesion for loose rock, loose material and shear zone is neglected due to these walls were not excavated by contour blasting and were exposed to natural weathering fro approx 30 years. Therefore, it is considered that due to the slope parallel stress release the cohesion along existing joints and fractures is neglectable.

Key outcomes included the ability to reduce berm widths (from 10m to 6m) and optimize slope angles (with reducing overburden excavation). In certain geometries, double benching was implemented (increasing the wall height) with addition of barrier to balance stability and access without compromising safety, thus increasing operational efficiency and economic feasibility (see **Equation 1**). For thin orebodies, with inclination of 40° to 50° it is more profitable to choose a pit design with-out benches. If the angle of the orebody is steeper than the friction angle of the contact and steeper than the angle of repose, every bench developed will fail along this contact. In that case, only a design without berms but with catch barriers can be considered (see **Figure 2**).

Moreover, with the system costs C_{sys}, the saved mining costs C_{min} and the value of the additional ore V_{ore}, the investment condition can be defined as follows in **Equation 1**:

$$C_{sys} < C_{min} + V_{ore} \tag{1}$$

If the costs of rockfall barriers are less than the saved mining costs and value of the additional ore, it makes economic sense to use the system. It is even possible that a deposit that was economically marginal could become more profitable by using barriers.

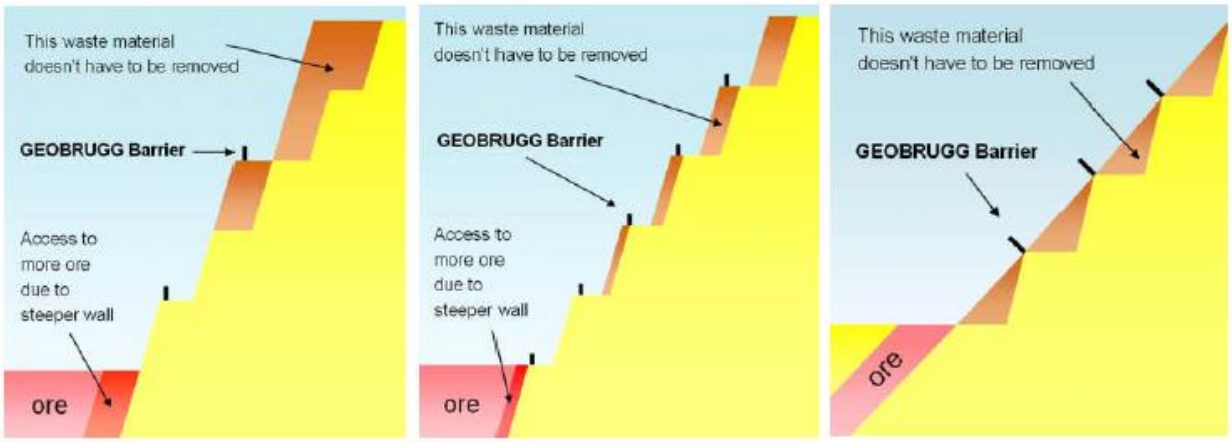

Figure 2. Advantages of using barriers in open pits; berm width reduction (left), increasing bench height with double benching (middle), omitting benches but using catch barriers as safety features (right)

The project also demonstrated that barriers effectively intercepted rockfalls and mudslides while high tensile steel meshes stabilized slopes near critical portals and haulage roads and in areas affected by heavy rainfall, where especially barriers with higher energy ratings (1500 kJ) proved as efficient protection thus demonstrating their dual-resilience validating the design through real-world performance.

Conclusion

The capacity of rockfall protection systems has evolved together with design and 3D simulation methodologies, only a few days ago, the Geobrugg rockfall fences have exceeded the 12MJ threshold, are undoubtedly the best alternative to the protective embankments. In the open pit design process, the reduction of the width of berms from the use of rockfall fences, is a useful, safe and very efficient practice that allows the increase in productivity, while the double berm combined with barriers is efficient against blast damage, additionally it is upright to note that in many cases it is more profitable, design the slopes using rockfall barriers without berms. The cost of the barriers location is much lower with respect to the benefit obtained in the production process and access to additional material ore. The practice of recent years has shown that rockfall barriers also work efficiently in areas of potential high-risk. In the case study of Mandai Quarry the combined solution, corroborates that the use of rockfall barriers and drapes, together with slope stabilization systems, allows a very efficient growth, into the safety factor, during the mining exploitation. In this paper, it was shown that high-tensile steel components are a suitable option to help to solve rockfall problems in open pit mines. In this application, a proper field test and component test is required to end up in a final designed and developed protection measure.

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Underground trial testing of NRE Support Rig

DIM-ESEE Conference
15th – 17th October 2025, Dubrovnik, Croatia

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Presenting author: Paulo Pleše

Keywords: NRE fleet, NRE Support rig, breast mining, utilization, efficiency.

Abstract

Narrow Reef Mining (NRM) is a method designed for extracting valuable minerals, such as platinum group metals and gold, from narrow ore bodies. The NRE fleet is a unique, innovative, electric robotic solution for underground mining, aiming to increase safety and productivity while reducing capital and operating costs (**Bohanek et al., 2023).** The Narrow Reef Equipment (NRE) made by DOK-ING consists of three main machines, each designed for a specific part of the mining cycle (drilling, cleaning and bolting) in narrow reef environments(**Bohanek et al., 2025**). The Support Rig is crucial for ensuring the safety of the mining process, but research clearly shows that the roof bolting activity is a significant bottleneck within the mining cycle (**Andrews & Pickering, 2010**).

(**a**) (**b**) (**c**)

Figure 1. NRE Fleet (a) NRE Drill Rig; (b) NRE Dozer; (c) NRE Support Rig.

The paper presents the results of trial efficiency testing conducted on the NRE Support Rig in two different mines located in South Africa. The Tumela mine is a major platinum group metals (PGM) operation positioned in South Africa, in the Thabazimbi District, Limpopo province. Anglo American Platinum, the world's largest producer of platinum, is the owner of the mine. Bokoni Platinum Mine is a significant platinum group metals (PGM) business based in Limpopo province in South Africa. The mine is entirely owned by African Rainbow Minerals which is the second largest PGM in the world. In both mine brest mininig layout is used for minining.

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Considering all factors influencing machine performance, Bokoni support rigs demonstrated superior results compared to those used at Tumela mine. While both sites employed identical machines, Bokoni implemented redesigned components that addressed prior performance issues.Additionally, Bokoni benefited from a more experienced operator base, many of whom had prior exposure to NRE and ULP systems. The site's revised training program further accelerated skill acquisition. Crucially, the Bokoni NRE team included four DOK-ING experts, who enhanced local capacity in machine operation, maintenance, and troubleshooting.

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Author's contribution

Paulo Pleše academic title): testing, formal analysis and original draft and writing. **Juraj Banić** (academic title): testing, and original draft and writing. **Vječislav Bohanek** (academic title): conceptualization and methodology. **Sibila Borojević Šoštarić** (academic title): conceptualization and review & editing.

All authors have read and agreed to the published version of the abstract.

Study of the stress-strain state of the massif during underground block leaching

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15th – 17th October 2025, Dubrovnik, Croatia

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Presenting author: Vsevolod Kalinichenko

Keywords: uranium ores, underground mining, pillar-crown, underground vertical strip leaching technology for shrinked uranium ores

Abstract

The presented work proves that, from an economic standpoint, it is advisable to apply the underground block leaching technology when mining deposits of low-grade uranium ores.

To implement this technology, the authors propose using strip mining with vertically arranged rooms. Adjacent vertical rooms can be separated by a temporary inter-level pillar (crown).

An analysis of current global uranium extraction technologies reveals the following (**Stupnik et al., 2022; Petlovanyi et al., 2019; Pysmennyi et al., 2020**). The world's leading uranium deposits, such as Coles Hill, Virginia, and the Colorado Plateau, are covered by the International Atomic Energy Agency (IAEA) classification. However, this classification does not account for changes in the stress-strain state of the host rock massif or the inter-room and inter-level pillars that come into contact with acidic solutions during uranium block leaching(**Stupnik et al., 2018; Bazaluk et al., 2022; Kosenko et al., 2024**).

The technology proposed by the authors of the study is called "underground vertical strip leaching technology for shrinked uranium ores", which is used for the first time in Ukraine. It works as follows.

In the vertically arranged rooms, uranium ore is blasted using borehole charges and then shrinked within the rooms. The next step involves breaking the pillars-crowns that separate adjacent vertical rooms, thus forming a continuous vertical strip of blasted uranium ore.

After that, from the higher-level workings, a sulfuric acid solution is fed onto the vertical strip of blasted uranium ore, and uranium is leached from the shrinked ore.

Current methodologies do not account for changes in the stress-strain state of the rock massif, the influence of the deposit dip, or the degree to which existing workings disturb the pillar-crown. Consequently, they are not designed to determine the safe thickness of the pillar-crown, and thus cannot establish the parameters for the proposed underground vertical strip leaching technology for shrinked uranium ores.

To study the stress-strain state of the surrounding rock massif and determine the stability of the pillar-crown when using strip leaching technology for uranium extraction, the authors employ a mathematical modeling technique utilizing the finite element method, **Figure 1**.

To determine the degree of influence of the acid solution's contact time on the strength of uranium ores and host rocks, a group of acid-treated cubes was examined.

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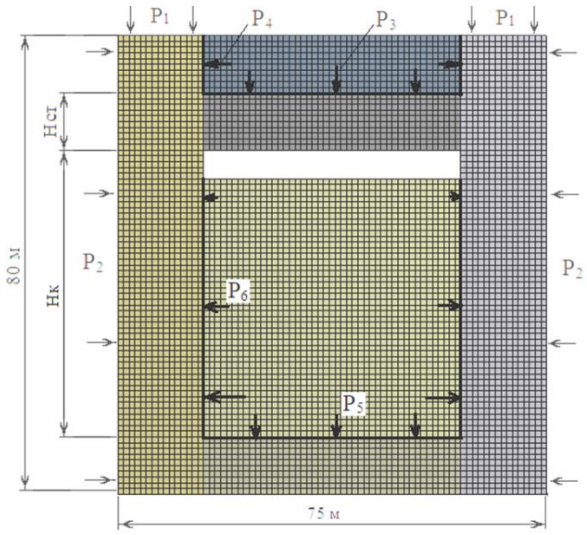

Figure 1. The area of the rock massif under study with a finite element grid.

The strength of uranium ore samples was tested using a hydraulic press connected to a computer. This setup recorded the load diagram for each sample and automatically registered the current stress and maximum load at the moment of its destruction, **Figure 2**.

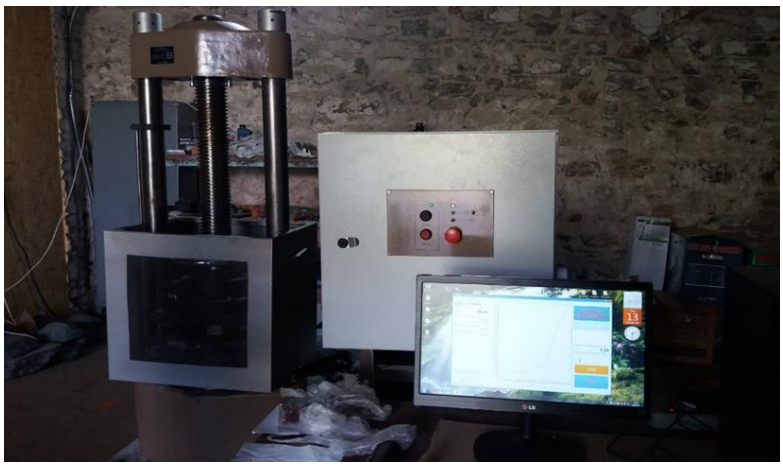

Figure 2. The strength of uranium ore samples was tested using a hydraulic press

The study aims to determine the patterns of change in the stress-strain state of the rock massif when implementing the technology of underground vertical strip leaching of shrinked uranium ores.

The stated goal was achieved by completing the following tasks:

- the global and domestic experience of leaching shrinked uranium ores was analyzed;
- the research was conducted on the effect of the acidic solution, used in underground block leaching, on the strength of uranium ores;
- the main principles of the technology of underground vertical strip leaching of shrinked uranium ores were developed and improved;
- an algorithm was developed to determine the stable parameters of loaded pillars when applying the underground block leaching technology for uranium ore extraction;
- the main patterns in the development of modern technologies for underground vertical strip leaching of shrinked uranium ores were substantiated.

Based on their research, the project authors develop fundamental theoretical foundations and establish new patterns of geodynamic stabilization of the rock massif. This work specifically considers the stress-strain state of the massif when employing underground block leaching technology for uranium ore extraction.

The authors determine the influence of the main acidic reagents on geotechnical factors and the overall geodynamic stability of the rock massif.

Theoretical foundations are developed for managing the state of the massif during the underground application of block leaching technology for uranium ore extraction.

The stability of technological elements is determined through mathematical modeling.

Highly efficient underground vertical strip leaching technologies for shrinked uranium ores are developed.

The core idea of this work is to:

- utilize the patterns of how main geotechnical factors influence rock pressure manifestations and the stability of artificial underground structures;
- account for dependencies of the stress-strain state of the rock massif on the structural elements of mining workings;
- develop various technologies for underground vertical strip leaching of shrinked uranium ores**.**

Working Hypothesis**:** Developing state-of-the-art measures for stabilizing geodynamic processes related to the stress-strain state of the rock massif is possible by implementing a high-tech strategy of underground vertical strip leaching of shrinked uranium ores.

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Author's contribution

Mykola Stupnik (Professor): methodology, validation and writing – original draft. **Olena Kalinichenko** (Professor): data curation, project administration and resources. **Vsevolod Kalinichenko** (Professor): conceptualization, funding acquisition, supervision, and investigation. **Volodymyr Pilchyk** (Postgraduate): formal analysis, visualization and software.

All authors have read and agreed to the published version of the abstract.

Improvement of explosion protection systems in coal mines due to gas-dynamic phenomena

DIM-ESEE Conference
15th – 17th October 2025, Dubrovnik, Croatia

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Presenting author: Oleksandr Holinko

Keywords: mines, explosion protection, methane, gas-dynamic phenomena, sensors

Abstract

The complex geological structure of coal deposits located in Ukraine, combined with high levels of gas contamination in the seams, their tendency to spontaneous combustion, and frequent sudden releases of coal, gas and rock mixtures, significantly increases the likelihood of emergencies. Incidents such as explosions of methane-air mixtures are particularly dangerous, threatening the lives of miners and the safety of mine equipment. One of the key reasons for such explosions is the improper or untimely operation of equipment, including stationary gas analysers, which are supposed to detect exceeding the permissible levels of methane concentration in the air of underground workings. These devices often do not react quickly enough or do not work at all in critical situations when the methane content in the air increases sharply **(Golinko & Kotlyarov, 2010)**. The most dangerous type of such sudden events is emissions, during which the methane concentration can rise to a maximum value of 100% in a very short time interval. At the same time, the rate of air saturation with methane sometimes reaches extremely high values - up to 5 per cent per second **(Golinko & Kotlyarov, 2010)**, which makes it impossible for most existing technical means to respond to the danger in a timely manner.

In modern conditions, considerable practical experience has been gained in the development and implementation of automated gas monitoring systems. At Ukrainian coal mines that mine seams prone to sudden gas-dynamic phenomena, ATB gas analysers are mostly used. These analysers are the main elements of the explosion protection system and continuously measure the volume concentration of methane in the workings and determine its growth rate. However, a significant problem with the use of existing gas analysing systems is their frequent triggering in cases where there are no real prerequisites for threatening situations. Such false signals lead to an unjustified suspension of the work process at coal mining facilities, which causes significant economic losses, reduces overall production, disrupts targets and complicates the organisation of mining operations. In addition, the technical means currently used to detect and prevent the consequences of sudden gas and dynamic emissions in high-risk mines do not fully meet modern requirements, in particular in terms of speed, reliability, resistance to external factors and maintenance **(Golinko & Kotlyarov, 2010)**.

In view of the above, further development of technologies in the field of automated systems for rapid response to hazards is extremely relevant, which involves both deep modernisation of existing devices and the introduction of fundamentally new engineering solutions for fast-acting protective equipment capable of effectively preventing the development of emergencies.

The analysis of existing approaches to detecting methane in mine air showed that the highest rate of detection of changes in the gas environment can be achieved by using optical absorption sensors **(Vovna & Zori, 2013)**. However, their use has a number of significant limitations, in particular, related to the high sensitivity to the impact of various

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factors on these sensors. One of the main constraints to the widespread use of these sensors is the high air dust content in the mine workings where gas analysers are installed.

Recent research work in the field of optical absorption measurement has made it possible to design compact, highly sensitive methane sensors **(Vovna & Zori, 2013)**. Such devices use a metal mesh that acts as a filter, inside which is placed a channel for optical reading. Given a filter wire diameter of 0.1 mm and holes with an area of 0.01 mm², the time constant of the devices is about one second.

In experimental prototypes of devices operating on the principle of absorption, it was possible to improve the dynamic sensitivity by introducing software signal processing methods **(Vovna et al., 2017)**. It was also partially possible to reduce the impact of negative external factors, including air pollution (**Vovna et al., 2010)**. However, the use of such solutions significantly complicates the design of analysers, necessitates the use of additional sensors with different spectral parameters, and does not solve the problem of automatic monitoring of the technical condition of the devices themselves. Thus, the question of creating a fully functional self-diagnostic system for methane analysers based on the optical absorption method remains open today.

Today, the vast majority of methane detectors used in automatic explosion protection systems are based on the relatively inertial thermocatalytic method **(Golinko & Kotlyarov, 2010)**. The popularity of this approach is due to the high accuracy of methane sensors, as well as their resistance to the effects of related external factors, such as high dust and humidity, changes in temperature conditions and gas composition.

The results of experiments and theoretical studies of thermocatalytic control devices **(Alekseev & Golinko, 2018; Alekseev & Golinko, 2020)** have significantly increased the level of durability and stability of such sensor systems. One of the advantages of thermocatalytic gas analysers is the ability to control their functional characteristics by adjusting the power supply parameters of the sensors. In combination with the capabilities of modern microprocessor-based computing devices, this allows for the self-diagnosis of the analysers' condition in remote mode, as well as for effective verification of the functioning of automatic power-off systems in case of danger detection.

In the framework of experimental studies **(Alekseev & Golinko, 2018)**, a method for monitoring the technical condition of stationary thermocatalytic gas analysers was developed and substantiated, which involves automatic verification of zero readings of devices by reducing the voltage applied to the thermogroup to a level at which the methane oxidation reaction on the working element stops. This makes it possible to determine the zero accuracy of the device without operator intervention. The use of modern digital technologies makes it possible not only to monitor the stability of zero readings, but also to automatically correct them in case of deviations. Additionally, the possibility of testing the sensitivity of sensors by analysing changes in their output parameters in the process of varying the electric current in the area of the so-called ‘plateau’ of the output characteristic, where a stable output voltage of the bridge is formed, was substantiated **(Alekseev & Golinko, 2020)**. Thanks to the use of modern microprocessor-based computing modules, it became possible not only to automatically evaluate the efficiency of primary converters, but also to promptly correct the readings of the analyser in cases of changes in its sensitivity. A functional algorithm and software have been developed to ensure continuous self-diagnostics of the device in operation.

It is worth noting that design improvements in the sensors themselves, such as reducing the size of the sensing elements and improving their geometry, have contributed to the improvement of their dynamic characteristics. Reducing the reaction time constant of thermocatalytic sensors and introducing new approaches to information processing have partially improved the overall dynamics of gas analysers **(Golinko & Kotlyarov, 2010)**. However, a complete solution to this technical problem has not yet been achieved.

In connection with the above, the purpose of this research is to find innovative ways to improve the efficiency and stability of automated explosion hazard monitoring systems under conditions of increased risk caused by gas-dynamic phenomena. It is easy to conclude that the best results in ensuring the maximum efficiency of the optical sensor response can be achieved when the radiation source and the receiving element are located directly in the area of the gas flow to be analysed. However, such a design configuration has a significant drawback: due to direct contact with the air-dust mixture, dust particles quickly settle on the optical surfaces of the source and receiver, which leads to distortion of measurement results, reduced accuracy of fixing the parameters of the gas environment and, as a result, loss of functionality of the device as a whole.

Given that such sensors are usually installed in areas with high dust levels, such as the cleaning areas of preparatory workings or the intersection of treatment and auxiliary workings, where the dust concentration in the air can reach hundreds of milligrams per cubic metre, the process of dust particle accumulation on the sensing elements is extremely intense. This makes it almost impossible to use unprotected sensors based on the optical principle. The use of protective elements or barriers, while reducing the rate of dust deposition, also negatively affects the response time of the device (increasing the so-called time constant) and creates additional difficulties in maintenance and cleaning of the device.

All of the above leads to the fact that to date, it has not been possible to create truly reliable and high-speed gas monitoring devices based solely on the optical method of methane detection. In this regard, as an alternative approach, we consider the solution proposed in **(Golinko & Kotlyarov, 2010)**, which presents the design of a combined analyser. In this variant, the main working element is a stable, albeit relatively slow, thermocatalytic sensor. Its signal is used to generate the system's information output: both a TV measurement signal and a command for an emergency power outage. In addition, it performs the function of correcting the results coming from a fast-acting, but more sensitive to contamination optical sensor. The optical sensor, in turn, provides a command to switch off the power supply when the maximum permissible methane concentration is reached or when this indicator changes too quickly in the air environment.

However, the disadvantage of this solution is that the accumulation of dust on the optical elements changes not only the measurement accuracy but also the overall sensitivity of the device. Therefore, even software signal correction does not fully compensate for changes in sensor sensitivity, which can lead to delayed or false alarms.

To solve this problem, an alternative approach is proposed: switching the optical sensor from the mode of fixing the absolute value of methane concentration to the mode of recording the rate of concentration increase during sudden gas-dynamic processes. This approach implies that in the absence of sharp changes in the methane concentration in the air, which are usually associated with sudden emissions, the main measurement function is performed by a thermocatalytic sensor, the signal from which is used to determine the level of gas pollution and generate a command to cut off power in case of exceeding the permissible limits. At the same time, the high-speed optical sensor is used only in cases where it is necessary to detect a rapid increase in methane content in a very short period of time. If the rate of increase in the gas concentration exceeds a certain critical threshold (for example, 1% per second), even with a relatively low current value of methane in the air, the system instantly generates an emergency shutdown command. If the growth rate is less intense (for example, in the range of 0.2-1.0 % per second), the current value of the thermocatalytic sensor and the growth value determined by the optical element are summed up. If the result exceeds the set safety limit, a safety shutdown is also initiated.

The proposed concept of increasing the responsiveness of the methane monitoring system is implemented on the basis of the existing design of the analyser, which has built-in functions of self-diagnosis, automatic zero calibration and sensitivity correction of the main thermocatalytic sensor **(Vovna et al., 2017; Vovna et al., 2010)**. A malinertial optical sensor is additionally integrated into this system, after which appropriate changes are made to the device's logic and software.

The developed analyser is implemented on the basis of an ATmega8 microcontroller, which provides a two-mode operation mode: a pre-setting (calibration) phase and an operational phase. The setup process is fully automated, without the participation of technical personnel, using a reference air environment and a control gas mixture with a given methane content (for example, at a concentration of 1%).

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All authors have read and agreed to the published version of the abstract.

Local Method for Dynamically Updating Ore Body Bedding Model Based on Machine Learning and Topographic Grid Reconstruction

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Keywords: geological modeling, ore body modeling, model updating, mesh reconstruction, machine learning, random forest.

Abstract

In the process of mineral extraction, geological exploration data serve as the foundation for constructing 3D models of mineral deposits structures. Modeling plays a critical role throughout the entire life cycle of deposit development, including deposit exploration, complexity analysis, mine design and planning, and production process management **(Deutsch, 2023).** Due to the limitations of technical conditions and exploration technologies, comprehensive data on ore bodies cannot be fully obtained through geological surveying to accurately describe the shape and distribution of the ore body. Therefore, ore body modeling is a dynamic process that is continuously refined as the geological database is updated. It must be gradually modified and revised in parallel with ongoing exploration and mining operations.

For instance, in the case of the Pivdenno-Bilozerske iron ore deposit, the characteristics of the ore body change continuously during extraction. Resource models become obsolete rapidly as geological information is collected along the mineralized zones. Consequently, short-term models must be regularly reconstructed to enhance modeling accuracy and optimize long-term planning. However, due to the complexity and uncertainty inherent is 3D geological modeling, it is often difficult to perform accurate mineral resource estimation, which significantly affects the efficiency and reliability of mine design and operation optimization. Therefore, the dynamic uprating of geological models has become a crucial task for optimizing mining operations.

In the context of continuous geological data updates, model reconstruction based on implicit modeling **(Sherstyuk, 1999)** is one of the possible solutions. Within this method, the geometric body is constructed from cross-sectional data. Mathematical functions can be used to represent the 3D surface model, which can be converted into a mesh model for visualization purposes. For geological models, if implicit models and boundary lines are available, they can be used as constraints for spatial interpolation, and the implicit modeling method can be directly applied for dynamic updating.

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However, the updated geological model can be constructed using various methods. For a similar model built using the contour splicing method **(Li et al., 2019),** it is difficult to update the model by using reinterpreted contour polylines.

For local updating of a geological model, the interactive mesh deformation method **(Huang et al., 2006)** may be a feasible approach. First, this method requires the refinement of mesh vertices in the area of interest on the surface of the updated mesh models, including both constrained and unconstrained points. Second, a target updated position must be specified for each constrained point, and the deformation constraints must be defined at the target position of each constrained point. During the deformation process, the coordinates of the unconstrained points are updated using the Laplacian deformation algorithm **(Sun et al., 2018).** Machine learning techniques offer major improvements in ore body forecasting, with the Random Forest algorithm **(Breiman, 2001)** demonstrating significant effectiveness in reducing prediction errors compared to linear regression, particularly in geologically heterogeneous environments. Finally, previous work on mining-technogenic object forecasting is in line with our findings and confirms the potential of mesh-based model updating based on dynamically acquired geological data (**Petlovanyi et al., 2021).**

The authors propose the use of a geological information database for predicting the spatial distribution of a mineral deposit. Unlike existing methods, the proposed approach is based on the manipulation of the vertices of the 3D surface mesh of the deposit. These points can be determined either instrumentally during geological exploration or predicted using regression analysis or the random forest algorithm.

The advantage of linear regression lies in its ability to generate an interpolation function that optimally describes the variability of the data. This function can also be used to determine the location for the development of mine workings intended to prepare the deposit for extraction. The main drawback of linear regression is the significant error margin when predicting data. To reduce the forecasting error, the random forest algorithm is employed.

To address the aforementioned challenges, we focus on a method of local updating of 3D ore body models based on real geological interpretation data obtained during mining operations. Based on mesh reconstruction, we consider the local update process of ore body models as a restructuring of mesh models guided by the predicted spatial distribution of the ore body using regression methods. This approach enables the automatic updating of the specified 3D ore body model using continuously enriched geological data. It provides an effective solution to the problem of high-frequency model updates during extraction and exploration and has broad potential for application and dissemination in geological modeling.

The proposed methodology was tested under the conditions of PJSC Zaporizhzhia iron ore plant, which develops the Pivdenno-Bilozerske iron ore deposit. The deposit has been accessed through vertical shafts and level drifts at the depths of 340, 400, 480, 560, 640, 740, 840, 940, 1040, and 1140 meters. The design capacity of the mine is 4.5 million tons of ore per year. Extraction and development works are carried out from the 840 meter level down to the 1140 meter level.

At the Zaporizhzhia Iron Ore Plant, a level-based preparation of the mine field reserves has been adopted, along with a level-chamber mining system involving sublevel ore blasting and subsequent artificial backfilling of the mined-out space using a hardening fill. The operational level height is 100 meters, and the chamber width is 30 meters. The chambers are mined in two stages in a checkerboard pattern. The forecasting methodology is based on the following approach.

At the first stage, a table of coordinates is created for the points belonging to the ore body. These data are obtained through instrumental measurements conducted in development or exploration workings. **Figure 1** presents the spatial representation of the ore body contours of the Pivdenno-Bilozerske iron ore deposit at the working levels. The points located along the contours indicate the intersections of the development workings with the ore body. The presented model is referenced to relative coordinates.

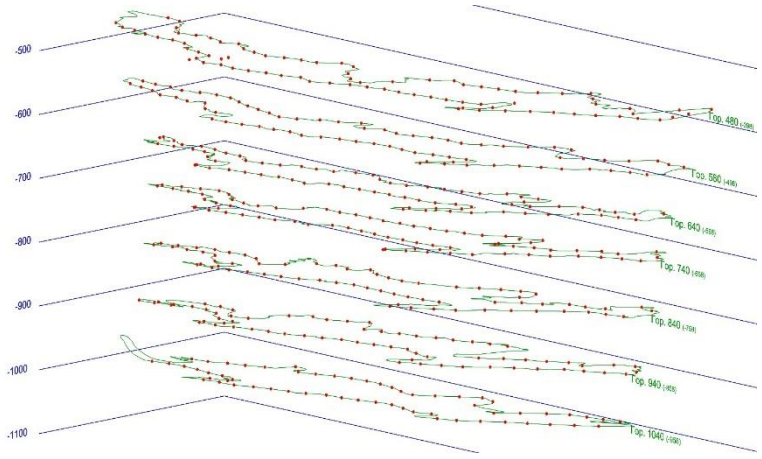

Figure 1. Technological contours of the ore body.

The coordinates of these points are used as a statistical dataset both for regression analysis and for further prediction of the ore body distribution using the random forest method. The data are divided into two separate samples corresponding to the hanging wall and footwall of the deposit (in the case of bedded deposits, these refer to the roof and floor surfaces of the seam, respectively). An example of the hanging wall data sample for mine surveying lines 3 to 10 of the northern wing of the mine field.

Unlike linear regression, the random forest method does not provide an explicit mathematical function describing the distribution of the ore body. Instead, it uses an ensemble of decision trees to predict values at specific spatial points, capturing complex, non-linear relationships in the data. This approach allows for more accurate identification of the predicted distribution points of the mineral. These points are then utilized to construct a detailed surface model of the deposit. A comparative analysis between the random forest method and the traditional deposit model for the South Bilozerka deposit at the forecasted depth of 1140 meters is presented in **Figure 2**.

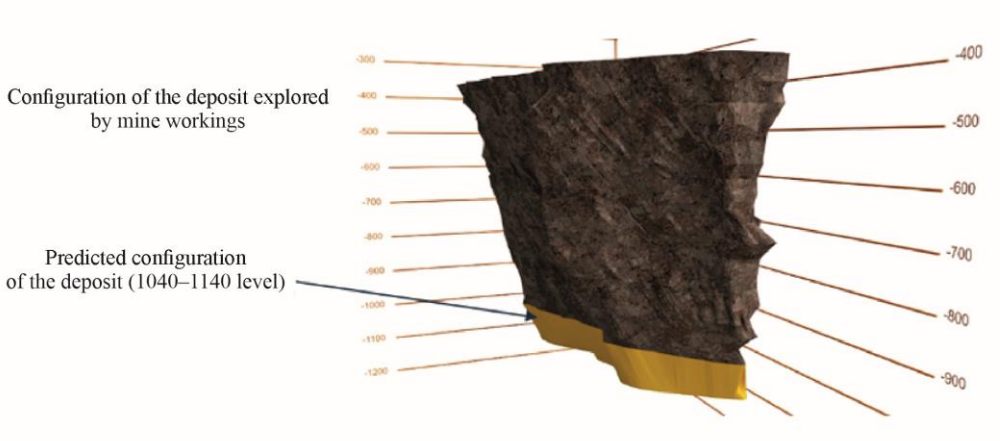

Figure 2. Predicted distribution of the South Bilozerka deposit at the 1140-meter level.

As can be seen, the data differ significantly within mine surveying axes 5 through 7 on the hanging wall, which may be attributed to the relatively large prediction step. Overall, however, the forecast can be considered satisfactory.

The integration of modeling tools into the entire life cycle of mineral deposit development demonstrates the growing importance of geological data management in modern mining. Modeling is no longer a one-time operation but a continuous process that adapts to newly acquired data and changing mining conditions. The proposed methodology provides a flexible framework for updating ore body models in real time, which enhances the accuracy of resource estimation and supports more informed decision-making in mine planning and operation. This approach contributes to greater adaptability, efficiency, and sustainability of mineral extraction processes.

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Oil Well Perforation Technologies with a Focus on Minimizing Damage to the Casing and Annular Space

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Presenting author: Oleksandr Pashchenko

Keywords: hybrid perforation technology, casing damage, annular space, formation permeability, adaptive energy control

Abstract

Perforation of oil and gas wells is a pivotal process in well completion, facilitating hydrocarbon flow from the reservoir to the wellbore by creating channels through the casing, cement sheath, and formation. Conventional perforation methods, particularly shaped-charge perforation, are widely used for their ability to form deep tunnels but often cause significant collateral damage, including cracks, deformations, and material loss in the casing, as well as compromised cement sheath integrity, leading to fluid leaks and debris accumulation in the annular space **(Chen et al., 2022; Maksymovych et al, 2021; Fituri et al. 2024)**. These issues reduce longevity, increase maintenance costs, and impair production efficiency, especially in complex geological settings like high-pressure, high-temperature (HPHT) wells or high-density formations. Alternative techniques, such as mechanical drilling, laser perforation, and hydro-abrasive perforation, offer distinct advantages, greater precision, cleaner channels, or reduced thermal damage, but face limitations in penetration depth, energy requirements, or effectiveness in hard formations **(Khomenko et al., 2023; Pashchenko et al., 2024; Ansari et al., 2015)**. The cumulative challenges of traditional methods, including microfractures, debris obstruction, and compromised zonal isolation, underscore the need for innovative perforation technologies that minimize structural damage while enhancing reservoir connectivity **(Robey et al., 2019; Ihnatov et al., 2023)**.

Efforts to mitigate perforation-induced damage have included directed perforation to align tunnels with reservoir stress fields, optimization of charge parameters to control penetration, and the use of advanced casing materials like high-strength alloys **(Xiao et al., 2015; Javora et al., 2008; Zhang et al., 2021)**. However, these approaches often address specific issues without comprehensively tackling the combined effects on casing, cement, and annular space. For instance, directed perforation enhances flow but does not reduce debris, and advanced materials increase costs, limiting adoption. Moreover, few studies integrate real-time adaptive control or predictive modeling to dynamically adjust perforation parameters, leaving a gap in achieving holistic damage mitigation. Fluid-structure interaction (FSI) modeling, which analyzes the interplay of fluid jets, shockwaves, and structural responses, offers a promising tool to optimize perforation processes but remains underutilized **(Nemati et al., 2025; Bahrami et al. 2009)**. This study proposes novel hybrid perforation technology that combines shaped-charge and mechanical drilling with adaptive energy control to reduce casing and annular damage while preserving perforation depth.

The hybrid system initiates tunnels using shaped charges and subsequently refines them with a mechanical bit, minimizing radial deformation and debris. The energy of the shaped charge is dynamically modulated using formation-specific data to avoid exceeding the casing's yield stress. The kinetic energy of the shaped charge jet is:

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$$E_c = \frac{1}{2} m_j v_j^2,$$

where are:
m_j – mass of the metallic jet (kg),
v_j – velocity (m/s).

Mechanical drilling parameters are optimized based on the unconfined compressive strength of the formation (σ_c):

$$T = k_r \sigma_c d_b^2,$$

$$F_a = k_a \sigma_c A_b,$$

where are:
k_r, k_a are empirical coefficients,
d_b – bit diameter (m),
A_b – bit contact area (m²).
σ_c – formation unconfined compressive strength (Pa)

To simulate interactions between explosive jets, fluids, and structural elements, fluid-structure interaction (FSI) modeling is used, incorporating the Navier-Stokes equations:

$$\rho_f \left(\frac{\partial v}{\partial t} + v \cdot \nabla v \right) = -\nabla p + \mu \nabla^2 v + f,$$

and the solid dynamics equation:

$$\rho_s \frac{\partial^2 u}{\partial t^2} = \nabla \cdot \sigma + b,$$

where are:
ρ_f – fluid density (kg/m³),
v – velocity (m/s),
p – pressure (Pa),
μ – viscosity (Pa·s), and f represents external forces (N), coupled with the structural dynamics equation:
ρ_s – structural density (kg/m³),
u – displacement (m),
σ – stress tensor (Pa),
b – body force (N).

Numerical modeling in ANSYS Fluent and COMSOL Multiphysics, using casing material parameters (e.g., σ_y = 550 MPa), cement strength (σ_{cc} = 30 MPa), and formation stiffness (E = 20 GPa), shows that the hybrid system decreases casing von Mises stress by 24.4 % compared to traditional methods. The peak stress is calculated by:

$$\sigma_{vm} = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2 - \sigma_x\sigma_y - \sigma_y\sigma_z - \sigma_z\sigma_x + 3(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2)},$$

where are:
$\sigma_x, \sigma_y, \sigma_z$ – normal stresses (Pa),
$\tau_{xy}, \tau_{yz}, \tau_{zx}$ – shear stresses (Pa).

Experimental validation was conducted using scaled P110 casing samples (σ_y = 758 MPa) embedded in cement and exposed to simulated downhole conditions (20 MPa, 80 °C). Ultrasonic and acoustic diagnostics, paired with post-test imaging, revealed that hybrid perforation reduces hole diameter and crack depth by 20.2 % and 44.8 %, respectively. Cement permeability was reduced by 57.1 % (from 0.28 mD to 0.12 mD), indicating improved zonal isolation. Similarly, formation permeability (k_f), evaluated via Darcy's law increased by 18 %, from 15 mD to 17.7 mD. Debris volume in the annular space decreased by 30 % owing to the post-charge drilling phase.

Compared to previous work by **(Robey et al., 2019)**, who reported a modest 11.4 % reduction in casing damage using alternative designs, the proposed hybrid approach demonstrates significantly improved performance. At work **(Nemati et al., 2025)** also emphasized the need to control debris accumulation, a challenge effectively addressed here. The novelty lies in integrating real-time adaptive energy modulation, which dynamically tunes charge intensity to formation properties, a capability absents in other approaches **(Chen et al., 2022; Zhang et al., 2021)**.

The limitations of this study stem from the controlled lab conditions, including uniform cement and formation properties. Downhole environments feature far more heterogeneity and thermal stress gradients, which may influence crack propagation and debris patterns differently. Therefore, field-scale validation is recommended to generalize results across various formations and stress regimes. Nevertheless, the findings suggest significant practical benefits: reduced casing and cement damage, improved formation access, and operational cost savings. In formations with $k_f < 20$ mD, these improvements are particularly relevant.

In conclusion, the proposed hybrid perforation system, supported by FSI modeling and experimental validation, effectively mitigates casing and annular space damage while enhancing reservoir connectivity. By reducing perforation-induced degradation and increasing formation permeability, this technology presents a compelling alternative to conventional completion methods in structurally sensitive or high-cost wells.

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Oleksandr Pashchenko (associated professor): conceptualization, methodology, writing and visualization. **Andrii Sudakov** (professor): project administration and supervision. **Valerii Rastsvietaiev** (associated professor): software and investigation. **Anita Proszkowska** (associated professor): methodological guidance & critical revision. **Santoshkumari Bohra** (student): data analysis & literature review.

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Investigation of the Role of Viscoelastic Properties of Drilling Fluids in Enhancing Rock Destruction

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Presenting author: Volodymyr Khomenko

Keywords: viscoelastic properties, drilling fluids, rock destruction, rate of penetration, storage modulus.

Abstract

The efficiency of drilling operations in the oil and gas industry, as well as in subsurface exploration, depends on optimizing interconnected processes, with drilling fluids (or drilling muds) playing a critical role. These fluids perform essential functions, including cooling and lubricating the drill bit, transporting cuttings to the surface, stabilizing the borehole, and controlling formation pressures **(Kozhevnykov et al., 2014; Jin et al., 2020; Stavychnyi et al. 2024)**. Beyond these well-established roles, the viscoelastic properties of drilling fluids, characterized by their ability to exhibit both viscous and elastic behaviors under stress, are increasingly recognized for their influence on the mechanical destruction of rock formations during drilling **(Pashchenko et al., 2024; Ihnatov et al., 2023, Biletskiy et al., 2019)**. These properties affect stress distribution and energy transfer at the rock-tool interface, potentially amplifying rock fracturing, particularly in challenging geological environments like hard or heterogeneous formations **(Khomenko et al., 2023; Maksymovych et al., 2021)**. Despite their importance, the specific contribution of viscoelastic properties to rock destruction remains underexplored, with limited studies addressing the underlying mechanisms or practical implications. Understanding and optimizing these properties can enhance the rate of penetration (ROP), reduce operational costs, and minimize environmental impacts, thereby improving overall construction efficiency.

The study of drilling fluids has long been central to petroleum engineering and geotechnical research, with extensive literature on their rheological properties, such as viscosity, yield stress, and shear-thinning behavior, which governs fluid flow under shear and stress. Foundational work by **Guo et al. (2021)** established models linking viscosity and flow behavior to cuttings transport and wellbore pressure losses, while later studies, like those by **Ronaes et al. (2012)**, emphasized shear-thinning properties for optimizing fluid performance across varying flow regimes. More recent research, including **Lyons et al. (2020)** and **Yang et al. (2023**), demonstrated how tailoring rheological profiles to specific formations (e.g., shales or carbonates) can enhance ROP, cuttings transport, and borehole stability. However, while rheology has been thoroughly investigated, viscoelasticity – particularly its role in rock destruction – has received less attention. Studies by **Ettehadi et al. (2022)** and **Werner et al. (2017)** provided initial insights, suggesting that viscoelastic fluids can enhance rock fracturing under high-pressure, high-temperature conditions by amplifying stress waves.

This study investigates how viscoelastic parameters – specifically the storage modulus G', loss modulus G'', and relaxation time τ – affect the mechanical interaction between drilling fluids and rock, ultimately influencing rate of penetration (ROP), torque, and energy efficiency.

To quantify the elastic and viscous contributions of drilling fluids, oscillatory shear tests were conducted using a rheometer to measure:

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$$G' = \frac{\sigma_0}{\gamma_0}\cos\delta; \quad (1)$$

$$G'' = \frac{\sigma_0}{\gamma_0}\sin\delta, \quad (2)$$

where are:
σ_0 – stress amplitude (Pa),
γ_0 – strain amplitude (dimensionless),
δ – phase angle between stress and strain (rad).

The viscoelastic relaxation time, a measure of how quickly a material dissipates stress, was calculated using:

$$\tau = \frac{\eta}{G}, \quad (3)$$

where are:
η – viscosity (Pa·s);
G – shear modulus (Pa).

Drilling fluids with varied polymer content (e.g., xanthan gum, polyacrylamide) were formulated to span a range of G' from 10 Pa to 100 Pa and τ from 0.1 s to 10 s. Rock samples – sandstone, limestone, and shale – were tested for their uniaxial compressive strength (UCS) using:

$$\sigma_c = \frac{F}{A}, \quad (4)$$

where are:
F – maximum force applied (N),
A – cross-sectional area of the sample (m²).

Drilling tests on cylindrical rock cores (50 mm × 100 mm) were performed under constant weight-on-bit and rotary speed conditions, using each fluid formulation. The ROP was determined by:

$$ROP = \frac{\Delta d}{\Delta t}, \quad (5)$$

where are:
Δd – depth drilled (m),
Δt – time interval (s).

Numerical simulations using finite element modeling incorporated generalized Maxwell models to simulate viscoelastic fluid behavior and Mohr-Coulomb failure criteria for the rock:

$$\sigma(t) = \int_{-\infty}^{t} G\,(t - t')\dot{\gamma}(t')dt', \quad (6)$$

where are:
$G(t)$ – relaxation modulus (Pa),
$\dot{\gamma}$ – shear rate (s^{-1}).

Results show that fluids with higher G' and τ consistently increased ROP and reduced torque across all rock types. For example, in sandstone, ROP increased from 5.2 mm/min using Fluid A ($G' = 10$ Pa, $\tau = 0.1$ s) to 8.5 mm/min with Fluid C ($G' = 100$ Pa, $\tau = 10$ s), representing a 63 % improvement. Simultaneously, torque dropped by approximately 19 %. These findings are statistically supported by a strong Pearson correlation coefficient for all rock types, confirming a robust link between viscoelastic properties and drilling performance.

Finite element analysis further revealed that higher-viscoelastic fluids generated greater shear stresses at the rock-fluid interface. Fluid C induced ~20 % higher shear stress than Fluid A in sandstone, correlating with enhanced ROP. These results align with prior theoretical frameworks that suggest stress amplification through elastic wave propagation in viscoelastic fluids **(Werner et al., 2017; Ettehadi et al., 2022)**, and extend them by validating these effects at ambient conditions.

Notably, the magnitude of improvement varied by lithology. Softer and more brittle rocks, such as sandstone (UCS ~50 MPa), showed greater sensitivity to viscoelastic enhancement than harder, more ductile formations like shale (UCS

~100 MPa). This suggests the importance of tailoring drilling fluid viscoelasticity to the specific mechanical properties of target formations – a novel insight with implications for lithology-adapted fluid design.

The experimental and modeling results demonstrate that viscoelastic parameters should be treated as primary fluid design criteria, on par with viscosity and yield stress, for optimizing drilling efficiency. Incorporating generalized Maxwell models into standard hydraulic simulators may better reflect real-world interactions, especially in formations with natural fractures or weak planes. Moreover, the observed reduction in torque implies that viscoelastic fluids may also lower energy consumption and reduce mechanical wear on drilling equipment.

In conclusion, this study quantitatively establishes that the viscoelastic properties of drilling fluids, particularly the storage modulus and relaxation time, significantly enhance rock destruction by amplifying stress transfer and facilitating crack initiation and propagation. These insights challenge existing drilling fluid paradigms and advocate for broader integration of viscoelastic behavior in fluid design and simulation tools, with the potential to substantially improve drilling performance across diverse geological conditions.

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Author's contribution

Volodymyr Khomenko (associated professor): conceptualization, writing and methodology. **Yevhenii Koroviaka** (associated professor): project administration, editing and formal analysis. **Andrii Ihnatov** (associated professor): investigation and software.

All authors have read and agreed to the published version of the abstract.

The influence of coal thermo-mechanical destruction on safety pillar's width in Underground Coal Gasification

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Presenting author: Ivan Sakhno

Keywords: underground coal gasification, pillars stability, safety pillar width, thin coal seam gasification, thermal stress.

Abstract

The most important component of sustainable development in recent years is the reduction of carbon emissions. The implementation of global commitments involves a planned reduction of greenhouse gas emissions and decarbonization **(UNFCCC: 2021)**. In the energy sector this can be achived primarily due to a decrease of fossil coal dependence, which is considered the main source of environmental pollution. The energy crisis caused by the war in Ukraine has shown the world's unwillingness to abandon coal **(Allam et al., 2022)**. However, an analysis of trends in global coal production shows that, contrary to expectations, the world is gradually increasing coal production, with its transfer to developing countries **(URL 1)**. According to various experts, if current trends in global energy will stay, coal will remain one of the key energy sources for at least the next ten years. In such conditions, along with the development of alternative "green" energy sources, technologies for reducing carbon emissions based on fossil coal usage as an energy resource are becoming increasingly relevant. In a global context, this is reflected in the increased scientific and engineering interest in underground coal gasification technologies (UCG).

Energy independence is one of the key factors for the survival of the economy during the war and development during the post-war reconstruction of Ukraine. Significant explored coal reserves of destroyed mines and promising areas which are, according to various estimates, guarantee the provision of the domestic market with this energy resource for a period of 100 to 250 years. At the same time, the integration of Ukraine into the European space includes reducing greenhouse gas emissions, which creates a contradiction between the necessity to increase generation, which can be realized by burning fossil coal, and obligations to reduce the carbon footprint. The solution to this contradiction is possible through the widespread implementation of UCG, which reveals the regional context of the relevance of this technology.

Nowadays experimental research is being conducted in underground gas generators and in laboratory conditions. Significant progress has been made in controlling the front of the UCG face; the optimal ranges of changes in the pressure rate of the blast mixture and the influence of the concentration of gases and steam on the gasification process have been determined; new methods of underground gasification have been introduced **(Dychkovskyi et al., 2025; Kostúr et al., 2018; Laouafa et al., 2016; Lozynskyi et al., 2024; Saik et al., 2016)**. Among the problematic issues limiting the use of UCG are the environmental hazards. First of all, there is a high risk of subsidence of the Earth's surface, flooding and water pollution due to the evolution of fractures in the overlying strata and the displacement of rocks above the UCG reactor cavities **(Sakhno et al., 2025)**.

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Parallel Controlled Retraction Injection Points (CRIP) method was investigated in this research. This method is more promising as it has higher efficiency of synthesis gas production, more stable gas production levels and increased coal utilization rates (**Lozynskyi et al., 2024; Seifi al., 2015)**. The stability of overburden rock over gasification panels with the CRIP method largely depends on the stability of the safety pillars.

Many scientists have studied the parameters of safety pillars in the case of using of the CRIP method **(Li et al., 2015; Najafi et al., 2014; Jiang et al., 2024)**. However, the influence of thermo-mechanical destruction of coal near production wells and injection wells on the width of the pillar between reactor cavities has not been sufficiently studied. Coal in the vicinity of a UCG panel are subjected to high temperatures which may be more then 1000 °C. This causes irreversible changes in the properties of coal, increased fracturing and a decrease in bearing capacity in the heat-affected zone. As a result of heating, the coal expands, creating additional thermal stress in the pillar. Thus, the functional pillar width becomes less than the geometrically designed width. The specified problem forms the explored surface of the study.

Numerical simulation is one of the best tools for comprehensive and qualitative understanding of the UCG process. In this study finite element method in Ansys software was used. The three-dimentional coupled thermal-mechanical numerical model was used. The Drucker-Prager model was used to simulate the behavior of rock mass. The Hoek–Brown Failure Criterion was used to calculate the properties of rock mass.

The mining and geological conditions of the Ukrainian Donbass served as the engineering background. The properties of coal seam and surrounding rocks were accepted in the simulation as averaged over the basin. The coal seam's depth varied from 200 m to 600 m. The length of the reactor cavities was 30 m. Stress-strain analysis and analysis of temperature distribution created the basis for understanding the mechanism of loss of pillar's bearing capacity and studying the laws of reduction of the functional width of the coal pillar depending on the depth. Figure 1 shows the distribution of temperature, thermal stress and minimal mechanical principal stress around the UCG reactor at a depth of 400 m.

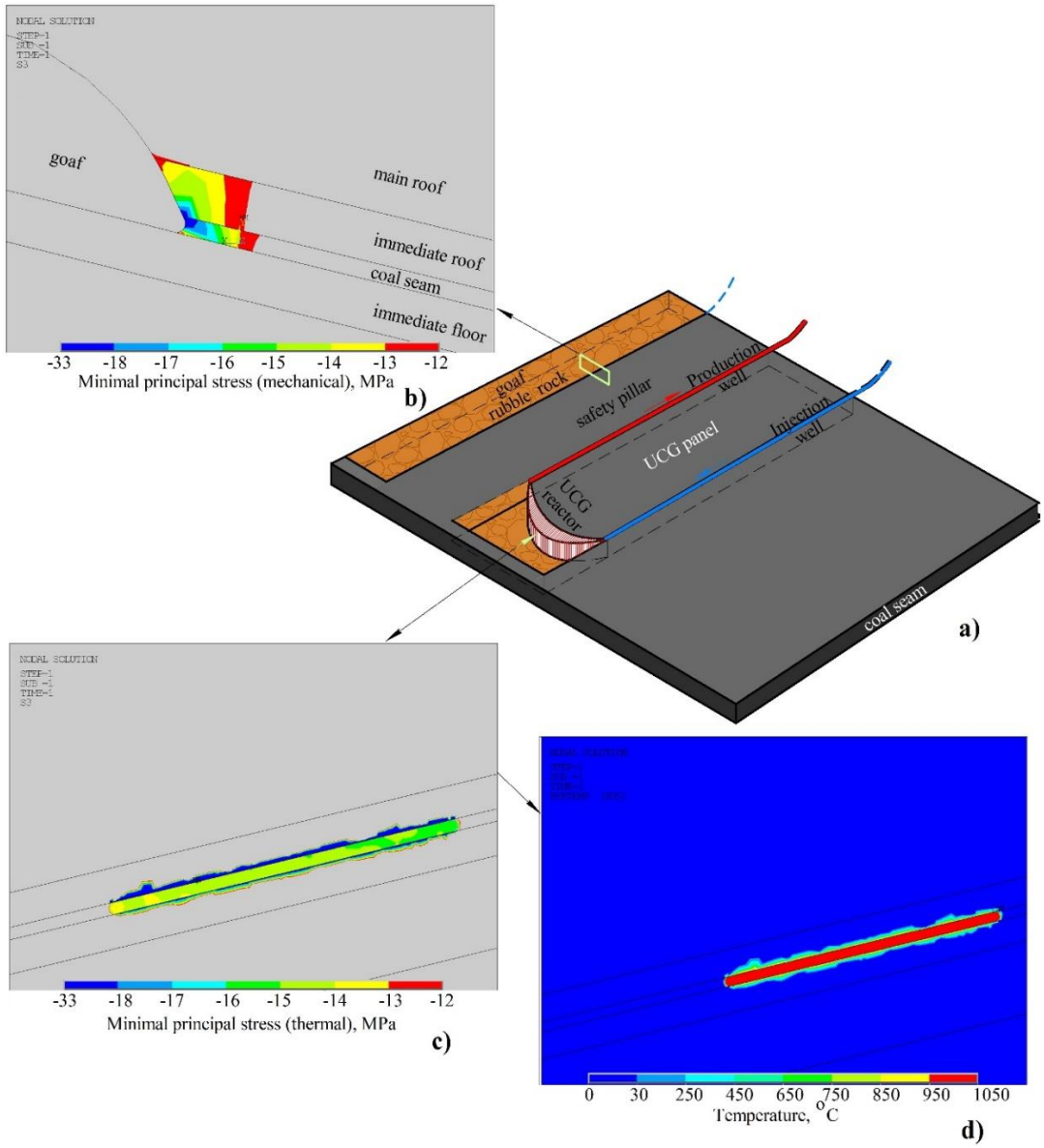

Figure 1. Procedure of the stress-strain analysis and analysis of temperature a) Scheme of CRIP method b) Minimal mechanical principal stress distributions c) Minimal thermal principal stress distributions d) Temperature distributions

It was found that the coal seam failure in the vicinity of production well and injection well leads to reduction in the functional width of the safety pillar. The greater the depth of the seam, the greater the width of the zone of thermo-mechanical destruction of coal in the pillar. A superposition-based algorithm is proposed for calculating the rate of reduction of the safety pillar's functional width depending on the depth under the coupled influence of mechanical and thermal stresses. The laws obtained in this study enable optimization of pillar width in the depth range of 200-600m. Thus makes it possible to increase the safety and reliability of UCG.

The authors believe that this study is another step towards improving the technology of underground coal gasification. This gives hope for the acceleration of the global green transformation in the energy sector and a sustainable future.

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Author's contribution

Svitlana Sakhno (PhD, Associate Professor): conceptualization, investigation, methodology, software and writing – review. **Ivan Sakhno** (DSc, Professor): project administration, resources, software, supervision and writing – original draft. **Serhii Bashynskyi** (PhD, Associate Professor): formal analysis, visualization and editing. **Munkhtsetseg Oidov** (PhD, Associate Professor) methodology, validation and editing

All authors have read and agreed to the published version of the abstract.

Development of engineering methods for strengthening slopes at the mining of watered titanium-zirconium pits

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Keywords: surface mining, titanium deposits, watered workings, safty slopes, soil stabilization.

Abstract

The research is devoted to substantiating practical engineering and technical methods for strengthening the slopes of the watered titanium-zirconium pits, which will allow in practice to reduce the risks of landslides and increase the efficiency of the mining enterprise.

The relevance of the research is associated with well-known cases in the world practice of mining operations, which resulted in significant displacement of sandy slopes of pits during heavy rains. The lack of proper drainage systems at mining enterprises led to oversaturation of the soil with water, which caused large-scale landslides, blocked production processes, and caused significant material losses. The examples demonstrate the importance of applying an integrated approach to preventing landslides of sandy soils of pit slopes, including using geotextiles, drainage systems, chemical additives, and terracing.

When conducting research, the following methods were used: general scientific and special methods such as theoretical (analysis, explanation, generalization) and modeling of stability parameters of mining ranges using specialized software Rocscience Slide, which allows you to perform slope stability analysis using various methods (Bishop, Janbu, Spencer, Morgenstern-Price, etc.).

Strengthening the slopes of the sides of watered pits for mining titanium-zirconium ores is a critically important task since the safety and efficiency of open-pit mining of promising watered deposits depend on its solution. Unstable slopes formed during mining operations can lead to rock slides, which complicates the mining process and creates a danger to workers and equipment. Successful strengthening of slopes requires taking into account hydrogeological conditions, mechanical properties of soils, and available strengthening methods. In addition, it is essential to minimize the amount of soil removal during stripping operations to achieve the effect of land conservation.

The research considered modern engineering methods for strengthening slopes, emphasizing their effectiveness in the context of flooded pit rocks. Particular attention is paid to anchor systems that provide additional slope support by securing them with steel or composite structures. This method can be especially effective in high slopes, where there is a risk of large volumes of soil collapse.

Analysis of slope stability in sandy-clayey soils using reinforcing structures is an essential task of engineering geology and geotechnics. The Rocscience software package is widely used to assess stability parameters and determine the need for slope reinforcement measures. Slide. This software product allows you to model complex engineering and geological conditions, take into account the influence of external loads and conduct slope stability analysis using various

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methods and conditions, take into account the influence of external loads, and conduct slope stability analysis using multiple methods (**Bishop, Janbu, Spencer, Morgenstern-Price, etc.).**

When performing studies on the calculation of stability parameters, the Bishop Method was used since it is the most effective method for solving most engineering problems and determining geomechanical stability. This method is more accurate than the method (Fellenius) and simpler and faster than complex methods (Morganstern-Price, finite elements). It is widely used in designing pit slopes and benches, where a circular cylindrical failure surface is possible.

The initial data for conducting research using modeling tools is the determination of possible parameters corresponding to the geometry of the slope, as well as the determination of its physical characteristics and preparation for further analysis. When performing the research, the mining and geological parameters of the development of the Motronivsko-Annivska section of the titanium-zirconium ore deposit **(Sobko et al., 2016)** is in commercial development **Table 1**.

Table 1. Physical and mechanical properties of rocks of overburden ledges of titanium-zirconium deposits.

#	Name	Unit weight, kN /m³	Clutch, kPA	Angle of internal friction, φ, degrees.
1	Forest-like loams	26.9	30	22
2	Red-brown clays	27	75	24
3	Plastered striped clays	23	50	30
4	Samara sands with clay	26	100	21.74
5	Sands of the Poltava series	26	25	30
6	Sand of the Kharkiv layer	20	30	35
7	Kyiv tier	27	10	20
8	Crystalline foundation	26	200	40

To determine the safe geomechanical parameters of the sides during pit operation, it is necessary to establish the maximum permissible angle of inclination of natural slopes, at which the slope stability reserve coefficient will remain within the allowable values. The critical value of the stability reserve coefficient in the studies is 1.15, below which the development of deformations and landslide processes is possible. The studies also study the possibility of further increasing the slope stability to increase the stability coefficient to 1.3 or more, ensuring the absence of deformations in the slope zone.

The calculation of the safety margin factor is performed taking into account the physical and mechanical characteristics of the overburden rocks of titanium-zirconium deposits (Table 1) with specified profiles for possible slope angles of the pit slopes from 14° (**Figure 1a**) up to 29° (**see Figure 1b**), which allows determining safe parameters of geomechanical stability of a given pit overall slope.

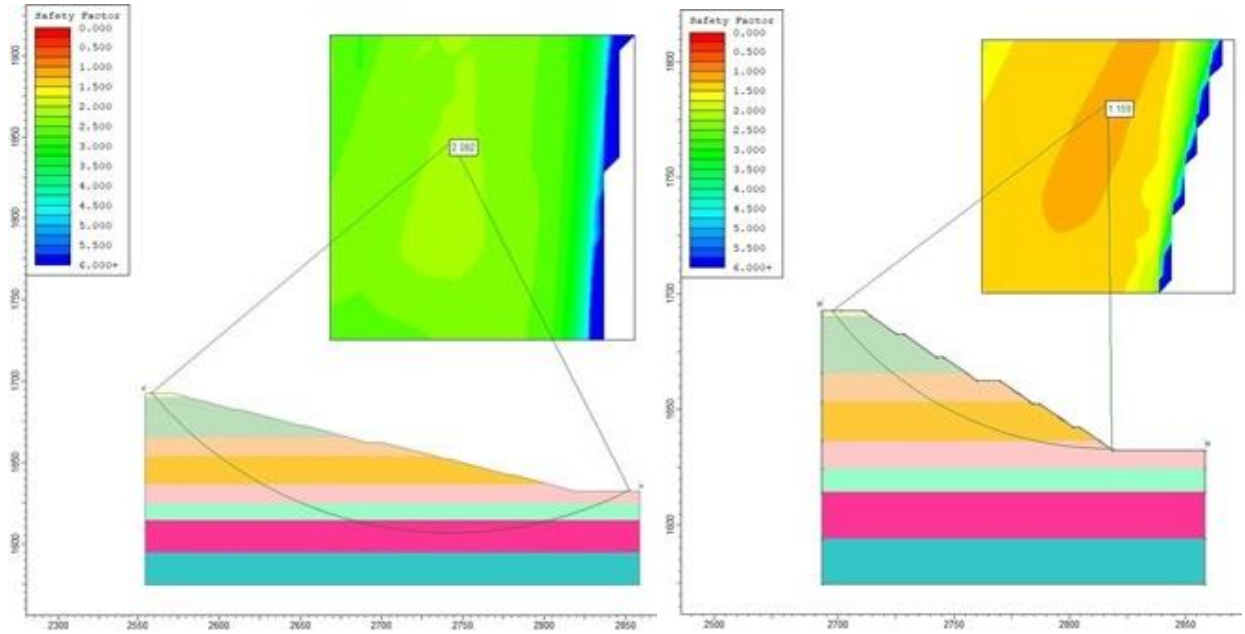

Figure 1. Results of Facrot of Safety calculation for overall slope a) 14° b) 29°.

Analysis of the calculation results (**Figure 1**) allows us to determine the influence of the slope angle of the overall slope of the titanium-zirconium pit on the safety factor. The obtained results of the safety factor indicator when changing the slope angle of the pit slope from 14 to 29º.

The obtained research results allow us to establish that increasing the height of the overburden slope during the development of titanium-zirconium deposits by 2.07 times from 14º to 29º leads to a decrease in the value of the factor of stability by 1.79 times from 2.08 to 1.16. Thus, it can be confirmed that the stability of the titanium-zirconium pits' overall slopes can be achieved only at small angles of inclination of their slopes or using engineering methods of strengthening.

Special software was used to investigate the effectiveness of a simple end-mounted system, such as mechanically secured anchor bolts or blind anchors. The slide provides the opportunity to simulate the stability of the mountain massif. When performing the research, the dependences of the stability reserve coefficient on the length of soil anchors (from 5 m to 40 m) were also established, which allowed for determining the effective parameters of engineering structures. The number of anchors taken in the research is 6 to 24 units. The distance between the anchors is 7 m to 20 m in the horizontal and vertical directions. Pull-out or failure load of the anchor mechanism (Anchor Capacity) in 150 kN.

The diagram of the quarry side in its normal state is shown in (**Figure 2a**), at the same time when using six anchors (**Figure 2b**) and 24 anchors (**Figure 2c**), which allows analyzing their location for further stability modeling work.

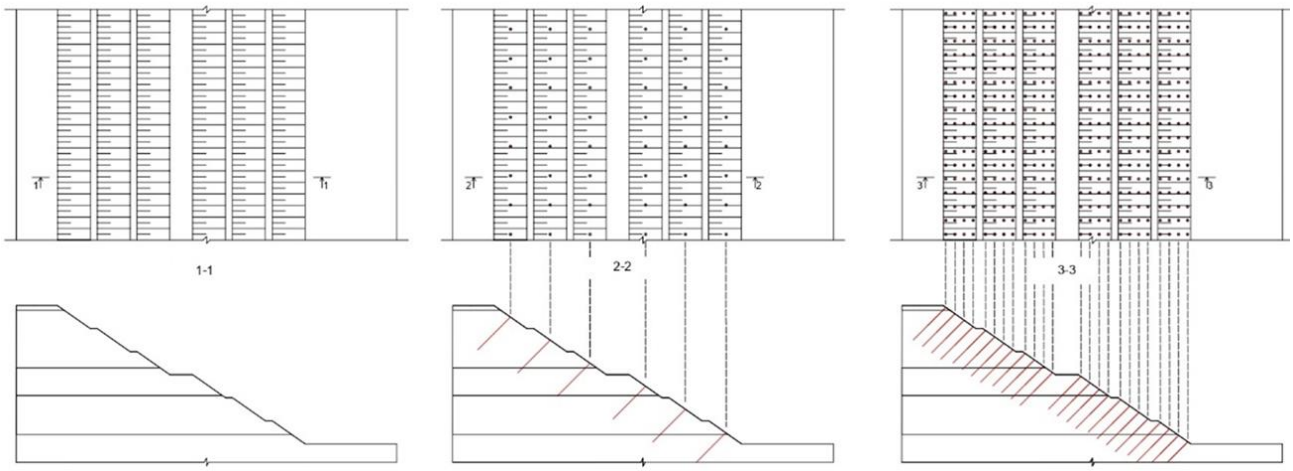

Figure 2. The overall slope of the pit a) Without installation of reinforcing elements, b) With the installation of a reduced number of reinforcing elements, c) With the installation of an increased number of reinforcing elements

Let us consider and determine the dependence of increasing soil anchors on the stability factor. The overall slope will be reinforced using soil anchors of various lengths. The length of the anchors is from 5 m to 40 m. Location: perpendicular to the slope. Quantity from 6 to 24 pieces. Distance between anchors: from 7 m to 20 m in the horizontal and vertical directions. Pull-out or failure load of the anchor mechanism (Anchor Capacity) in 150 kN. The results of the research are presented in **Figure 3**.

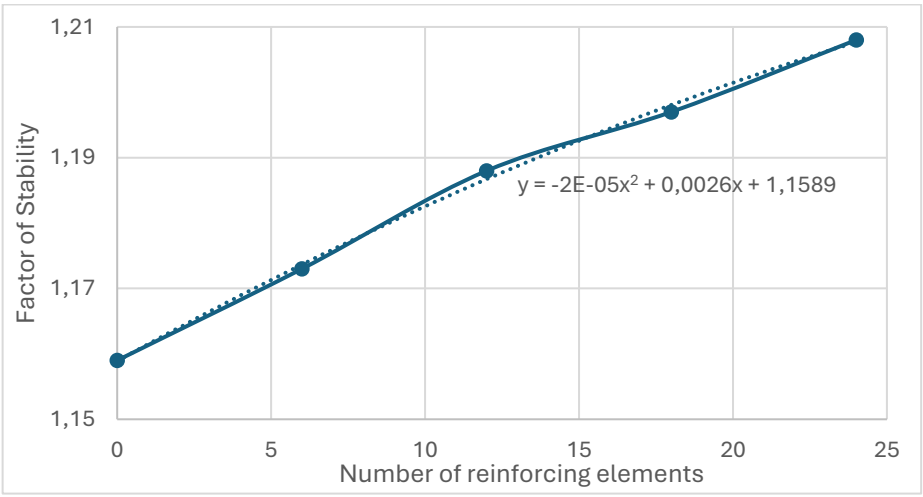

Figure 3. Dependence of the Factor of Safety on the number of reinforcing elements

According to the obtained research results (**Figure 4**), increasing the number of reinforcing elements on the overall slopes of titanium-zirconium pits will lead to their strengthening and an increase in the safety factor. The research that

was conducted allows us to state that with an increase in the number of anchors from 0 to 24 units, the safety factor of the slope of the side will increase by 4.2 % from 1.16 to 1.21. Thus, using this engineering method of strengthening sandy-clay soils can occur in limited cases for a slight increase in the safety factor of the overall slopes of the pits.

Given these factors, it is advisable to consider alternative methods of slope reinforcement, such as bored piles, reinforced embankments, geotextile and geogrid structures, or combined slope reinforcement systems. Further research should be aimed at choosing the optimal solution by taking into account economic feasibility, environmental safety, and the durability of structures.

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Author's contribution

Oleksii Lohznikov (Professor, Dr. Sci. (Tech.): conceptualization, investigation and supervision. **Carsten Drebenstedt** (Professor, Dr.): methodology, resources, supervision, validation. **Anton Bondarenko** (Post graduate student): data curation, formal analysis, original draft and writing.

All authors have read and agreed to the published version of the abstract.

Parameters of the optimal sections of gate roads in the Western Donbas mines within the loosened layered rock mass

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Presenting author: Ivan Sadovenko

Keywords: rock mass, supporting parameters of gate roads, mine working floor heaving, stress-strain state, rheological changes in rock strength.

Abstract

Construction and operation of gate roads in geometric coordinates of the layered nonuniform carbonaceous rock mass close to transverse-isotropic characteristics is among the current theoretical and practical trends of mining progress. In the context of the trends, geotechnologic substantiation of the efficient preparation of extraction pillars taking into consideration their parameters correlated with parameters of gate roads in time and space has the most significant impact on technical and economic efficiency of coal mining **(Bondarenko et al., 2018; Pivnyak et al., 2015)**.

Over recent years, following research findings are worth mentioning and emphasizing since they have met with recognition by scientists and have been implemented:

- geomechanical forecast of in-seam working rock floor heaving with explanation of the process mechanism under the varied mining and geomechanical situation and development of such geotechnical measures minimizing negative operational factors as well as improving the possibilities to reuse the gate roads **(Bondarenko et al., 2014; Sakhno et al., 2023; Vlasov et al., 2022)**;
- analysis of stress-strain state of longwall-gate road connection in the format of a static phase of the gate road parameters as well as their temporal changes under the influence of the advanced stope, and measures of geotechnical control of the process to maintain the opening section for its reuse **(Rahimi et al., 2020; Snihur et al., 2022)**;
- geomechanical and technological substantiation of the measures maintaining sections of gate roads while mining gently sloping seams in the layered rock mass with transverse-isotropic heterogeneity in terms of strength characteristics **(Małkowski et al., 2016)**.

In the context of the formulation and results, cumulative analysis of the mentioned theoretical and practical trends makes it possible to consider them as positive; however, a remark is reasonable as for geotechnical locality of research concerning the specific objects as well as insufficient analytical generalization of problems (or their lack) involving the required coordination of theory and practice.

Consequently, the research purpose is to optimize geometrical configuration of a road drift section under the conditions of the layered rock mass losing its strength in time and space, being impacted by stress redistribution during development.

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The task formulation is quite logic as for elimination of geotechnical locality of the available solutions to select a relevant configuration of a gate road section in terms of the layered rock mass losing its strength in time and space being impacted by stress redistribution during development. It can be performed while correlating physicomechanical description of phases of conditionally radial compaction of a mine working section with support leg deepening into its floor or because of rheological change in rock strength.

While selecting rational support design, one should take into consideration regularities of rock pressure manifestation; characteristics and structure of wall rocks; and nature of their interaction with the support.

In Western Donbas mines, rock pressure in gate roads is manifested mainly as floor heaving. If soft wall rocks are available and compression boundary is 7 MPa – 30 MPa then gate road floor heaving does not die out becoming 0.5 m – 1.0 m and more at the mining depth exceeding 300 m. Hence, a floor blasting after gate road construction by an extraction pillar length (1200 m – 1400 m) becomes a significant share of the total length. Both practice and research by the authors have helped identify that a floor blasting activates rock-heaving process again; thus, the necessity arises to repeat blasting before mining starts. In this regard, wall pressure impact results in the following. The unrestrained support legs are displaced inside a mine working by 0.2 m – 0.4 m provoking deformation of joints.

Efforts to strengthen the supports using a reverse arch increase their steel intensity as well as preparation period of an extraction pillar. Moreover, practices have also helped understand such a reverse arch cannot prevent from a floor heaving within a longwall-bearing zone; in addition, labour intensity and cost of the deformed elements increase many times.

If rock displacement is more than 300 mm then Standards recommend using a five-link support. Nevertheless, real-life in Western Donbas mines show that in practice deformability in a lower joint is not implemented. The abovementioned can be explained by the fact that if wall rocks are soft then a support leg deepening into a mine working floor is 100 mm – 300 mm to 600 mm – 700 mm depending upon the rock strength as well as pressure on the support. It is also known that while deepening, legs are pinched within the basis of the undisturbed floor rocks, which increases their resistance to lateral rock displacement. Consequently, taking into consideration the effect of a leg deepening into mine working floor, three-link support deformability achieves deformability of a five-link one.

Relying upon the stated, it is expedient for Western Donbas mines to increase height of gate roads at the expense of making longer support legs to compensate the most intensive rock displacements from a floor, which will help stabilize an equilibrium state of the rock periphery and provide the required effective section of a mine working.

To identify a value of the required support leg extension, we have applied a result of analytical solution as a boundary strain situation with the pronounced rock loosening:

$$U = kr_o \tag{1}$$

where are:
U – a mine working periphery displacement,
k – the generalized proportionality factor demonstrating geomechanical interaction between conditionally radial mine working and rock mass,
r_0 – an equivalent radius of the mine working.

Formula (1) potential to be used for the problem solving is supported by following conditions:

- significant displacements within a gate road periphery result from a loosening zone impact (i.e. extreme deformations);
- configuration of support peripheries as well as resistance value does not impact practically loosening zone dimensions and displacements inside it defining meanwhile distribution of the displacements throughout the mine working boundary which is confirmed by numerous field data;
- within the rock mass under loosening, time factor influence is demonstrated the most accurately owing to full-scale measurements since the known solutions take into consideration rheological process in limit load.

In the context of the mentioned conditions, actual data by more than twenty measuring stations mounted in gate roads have been processed. As a result, following empiric ratios with 0.85 – 0.97 correlation coefficients were derived:

$$\Delta S_i = 4.54h_i - 0.09h_i^2 + 0.38 \tag{2}$$

$$h_i = (a_i \ln T + c_i)10^{-3} \tag{3}$$

where are:
S_i – decrease in a gate road section area, m^2,
h_i – value of a gate road roof heaving, m,
T – time from the gate road construction start till to the moment under consideration, days,

a_i, c_i – regression parameters.

From the viewpoint of geometry, we can obtain:

$$r_0 = \left(\frac{S_p + \Delta S_0 + \Delta S_T}{\pi} \right)^{\frac{1}{2}} \tag{4}$$

$$\Delta S_0 = \pi U^2 \left(\frac{2}{k} \right) - 1 \tag{5}$$

where are:

S_p – the required operational area of a gate road section,

ΔS_0, and ΔS_T – decrease in the section area corresponding to conditionally instantaneous displacements, and time interval T,

r_0 – radius of S_0 section reduced to a circle.

For conditionally instantaneous displacements in the form of (1), and under further decrease of a gate road section (2, 3), following semi-empirical expression has been obtained during joint solution of formulas (1 and 5):

$$r_0 = \left[\frac{S_p + 10^{-3} a_i \ln T (4.54 - 9 a_i \ln T)}{\pi \left(1 - 2k + k^2\right)} \right]^{\frac{1}{2}} \tag{6}$$

Stable connection between a_i parameter and lithological and structural criteria has been defined for (3) ratios:

$$\Pi = \frac{\sum_{i=1}^{n} \frac{l_i + m_i}{m_i}}{n} \tag{7}$$

where are:

l_i – distance to i^{th} sandstone seam roof over a mine working (or to a floor of a seam underlying the mine working),

m_i – the i^{th} seam thickness,

n – the number of the seams being a_i – 93.5 if $\Pi \leq 1.15$; a_i – 63,5 within $1.15 < \Pi < 1.30$ range; and a_i –38.7 if $\Pi \geq 1.30$.

The required extension of support legs is:

$$l = \frac{\pi r_0^2 - S_{\min} - bA}{A} \tag{8}$$

where are:

S_{min} and A – the specified standard gate road section and its width respectively,

b – a value of leg deepening into the loosened floor.

The deepening value can be calculated using Schleicher formula connecting subsidence of tantalizingly loaded die with deformation modulus of a floor basis.

In such a way, it has been identified that displacements of gate road peripheries being unacceptable for practice are shaped if wall rocks experience loosening and extreme deformation zone arises defining distribution of the displacements throughout a mine working periphery. In this regard, time factor influence is demonstrated the most accurately owing to full-scale measurements. Relying upon data by more than twenty measuring stations, empiric ratios with 0.85 – 0.97 correlation coefficients were derived. Moreover, stable connection between non-linear regression and lithological and structural criterion of enclosing rocks as well as its connection with the required extension of support legs to compensate gate road floor heaving.

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Author's contribution

Ivav Sadovenko (professor): conceptualization, research, methodology, original draft, and writing. **Serhii Vlasov** (professor): research, methodology, original draft, and writing. **Vladyslav Vlasov** (engineer): data processing, formal analysis, and visualization. **Stanislav Hroma** (engineer): checking, reviewing, and editing.

All authors have read and agreed to the published version of the abstract.

Study of the Condition of Underground Facilities of Various Purposes Utilizing High-Precision 3D Scanning

DIM-ESEE Conference
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Presenting author: Serhii Pysmennyi

Keywords: handheld scanner, working, stability, stresses, strains.

Abstract

Since 2014, russia's aggression in Ukraine has caused significant damage to both surface and underground mining facilities, as well as dual-purpose infrastructure. Under martial law, a critical need has emerged for the rapid restoration and construction of damaged facilities of various purposes to ensure the effective operation of underground mining enterprises. Since the full-scale invasion in 2022, the annual productivity of mining enterprises has nearly halved. This decline is primarily due to a shortage of human resources and the inherent risks of storing the necessary quantities of explosives and equipment, which are essential for uninterrupted underground mineral extraction, on the surface.

This challenge can be addressed through two primary strategies: construction of artificial underground facilities for explosive storage and production, and for maintenance of mining equipment (**Azaryan et al., 2018; Smoliński et al., 2022**); and expanded employment of imported high-performance self-propelled machinery to partially compensate for human-related factors (**Bazaluk et al., 2022; Stupnik et al., 2021; Pysmennyi et al., 2020**).

An analysis of operations at the Kiruna mines (Sweden) and Zaporizhzhia and Kryvyi Rih iron ore combines (Ukraine) reveals that employment of high-performance self-propelled equipment significantly enhances labor productivity. This enables a decrease in the overall workforce in underground mining and ensures the required annual mine output. However, most Ukrainian mines still rely on traditional domestic drilling equipment, with all development, preparation, and stoping projects specifically designed for this type of machinery.

Switching to high-performance self-propelled equipment in mining requires not only innovating mining systems, but also creating underground rooms for keeping and servicing this equipment (**Bazaluk et al., 2021; Kosenko, 2023; Kuzmenko et al., 2023**). The authors of the article present their own options of novel mining systems utilizing imported self-propelled equipment. These systems encompass both open stope mining and induced caving methods and are currently implemented at the Zhovtneva mine of Zaporizhzhia Iron Ore Combine and, to a limited extent, within Kryvyi Rih iron ore basin.

For the effective implementation of these advanced mining systems in Kryvyi Rih iron ore basin, mining enterprises need to create additional underground rooms on the haulage level to service imported self-propelled equipment. Based on the geological and mining characteristics of the deposits and the substantial depth of underground operations (over 1200 m), creating these additional underground rooms is only feasible in stable rock formations, specifically granites or amphibolites. This typically restricts their deployment to the shaft bottom area. However, after five years of operation at this depth, the surrounding rock massif has experienced partial disturbance due to considerable rock pressure, which in some areas surpasses 250 MPa.

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To accurately assess the stability of the rock massif surrounding underground workings, it is essential to develop a comprehensive model of the underground level. This model should precisely reflect the current condition of existing workings. Developing such a mathematical model necessitates significant underground data collection. The obtained data can then be processed in various computer modeling software, including but not limited to: *Tinkercad, SketchUp, Fusion 360, Blender, SolidWorks, AutoCAD,* and *K-Mine*. It should be noted that building this mathematical model demands not only an accurate spatial representation of all mining objects but also a thorough consideration of the technical condition of each individual working.

To ensure high-quality studies of the condition of underground facilities of various purposes, the authors propose utilizing high-precision 3D scanning and modeling. This advanced method enables identifying the geodynamic stabilization patterns of the rock massif during construction of underground facilities including safe underground refueling stations for mining equipment; underground service and repair facilities for self-propelled mining equipment; construction of technological workings, all while precisely taking into account the stress-strain state of the rock massif.

Currently, the study of underground objects is being significantly advanced through the use of a state-of-the-art handheld high-precision 3D scanner that enables rapid 3D scanning and modeling of underground structures, offering capabilities unparalleled in Ukraine. The results of the studies conducted using this innovative 3D scanning technology are presented in Fig.1.

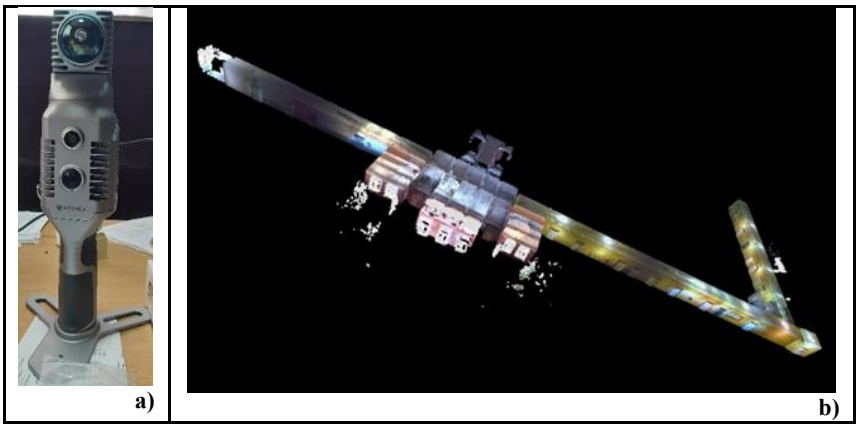

Figure 1. A fragment of the scanning results when using a handheld 3D scanner
a) handheld 3D scanner b) 3D model

During the study conducted with the 3D scanner, a substantial data set is generated and securely stored in the cloud. This collected data then undergoes further processing using relevant software packages, selection of which depends on the specific research objectives. Furthermore, this data can also be utilized to track and analyze dynamic changes within the rock massif that occur over time as the deposit undergoes continued development.

The obtained data is then imported into specialized software packages (e.g., ANSYS) to determine the stress distribution around the underground working within a predefined area. The results of this analysis are presented in Fig. 2.

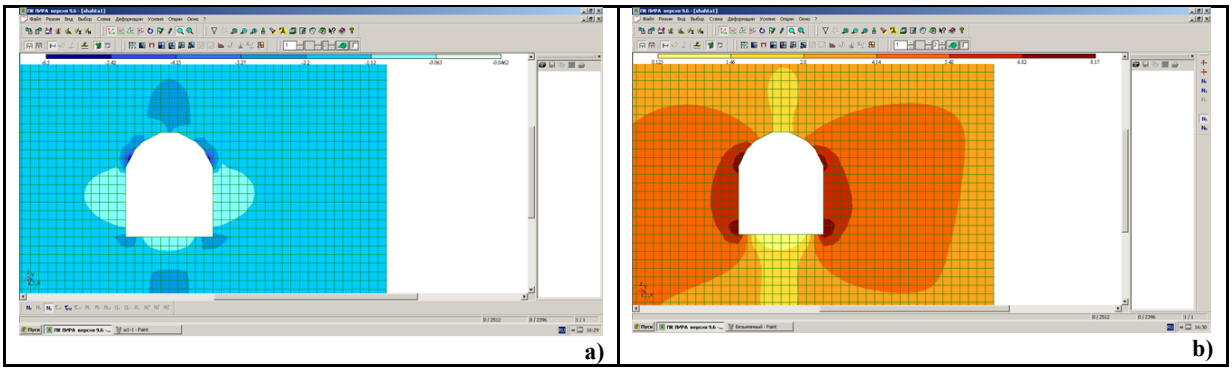

Figure 2. Stress distribution around an underground working at a depth of 1390 m
a) vertical stresses b) equivalent stresses.

The calculation results provide a foundation for a detailed analysis of the stress-strain state of the model. This analysis is crucial for developing effective measures to stabilize geodynamic processes taking into account the stress-strain state of the massif, especially during rapid construction of underground facilities depending on mining, geological and technical conditions of their deployment.

The results of the study have significant and diverse applications, namely: rapid restoration and construction of underground technological facilities; construction of strategic underground plants for producing and storing explosives; construction of underground facilities for light and medium equipment repair and refueling stations for self-propelled

mining equipment; restoration and construction of war-damaged industrial and technological facilities utilizing high-precision 3D scanning and modeling.

It should also be noted that while studying objects deployed underground or in hazardous areas, works are typically conducted by male personnel, the subsequent processing of data and 3D modeling can effectively involve female specialists. This helps to address the current shortage of human resources, a critical concern during the ongoing state of martial law in Ukraine.

The ability to repeatedly utilize the study results obtained through high-precision 3D scanning, coupled with their compatibility with various software packages for diverse applications, presents a highly promising outlook. This approach aligns perfectly with the guiding FAIR (Findability, Accessibility, Interoperability, Reusability) principles, ensuring that the valuable data generated can be readily discovered, accessed, integrated, and reused for future research and practical solutions.

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Author’s contribution

Serhii Pysmennyi (Associate Professor): conceptualization, funding acquisition, supervision, and investigation. **Dmytro Brovko** (Professor): data curation, project administration and resources. **Mykhailo Fedko** (Associate Professor): methodology, validation and writing – original draft. **Svetlana Panova** (Associate Professor): formal analysis, visualization and software.

All authors have read and agreed to the published version of the abstract.

Comparative measurements of active concentration of radon (Rn) in air

DIM-ESEE Conference
15th – 17th October 2025, Dubrovnik, Croatia

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Presenting author: Hrvoje Vukošić

Keywords: air quality in mines, Rn radon in air, prediction/forecast methods

Abstract

Radon (Rn) occurs as a chemically inert (noble) gas, heaviest gas by molar mass in nature, present in soil, water, and air. Rn is a natural radionuclide, with generation and decay through radioactive decay of radium ^{226}Ra in the uranium series, with a half-life of $T_{1/2}$=3.823 days and a decay constant λ_{Rn} = 2.0984·10-6 s^{-1}. During this process, ionizing radiation is emitted as α- (alpha) particles (the nucleus of a helium atom with an electric charge of +2e) and this can be detected electrically **(George, 2008; 'Nuclear Data – Table', n.d.).** In the following text, prevailing radon isotope ^{222}Rn will be simply referred to as 'Rn'.

Under normal conditions, Rn represents the largest source of the total dose of ionizing radiation that a person receives over the year, and is a significant parameter of air quality (*eng. Indoor air quality/IAQ*) **(Joshi, Aswal, & Chandra, 2024).** Rn poses a significant health risk since it can be inhaled as a gas and the chain of radioactive decay of Rn atoms ends with lead (^{206}Pb) **('Health Physics', n.d.).** For this reason, radon is included in the parameters of air quality in enclosed spaces, as concentrations in open spaces are very low. Therefore, it is necessary to identify locations and objects with elevated levels (parts of buildings and mines where people reside or work), which can only be achieved by measurement of the active concentration of Rn. Measurements are conducted at micro-locations and are most reliable and accurate in long-term (1 year), which requires a large number of measurements and a long time for conducting the measurements. **(Font et al., 1999; Tsapalov & Kovler, 2024)** The active concentration of Rn is measured in Bq/m^3 or pCi/l (1 Bq/m^3 = 0.027 pCi/l). Reference level for the annual average active concentration in the air is 300 Bq/m^3, which is the highest allowed annual average value of active concentration in indoor air. **('Directive 2013/59/Euratom - EU-OSHA', n.d.).** Measuring radon is also applied in predicting earthquakes or volcanic activity, exploring uranium ores, locating underground tectonic faults, monitoring the migration of underground gases over large distances, groundwater, and monitoring atmospheric circulation. **(Röttger et al., 2022)**

Rn in buildings comes from soil gas, groundwater, outdoor air, and water and gas installations and is transported/migrates over greater distances. The concentrations of Rn in the air (within a closed building) are variable as they depend on several influences, such as: atmospheric conditions, geological composition of the soil, construction properties, seismic activity of the area/location, and ventilation**. (Carslaw, 2007; Hess, 1953)**

(Active) concentration of Rn is measured passively (for long-term) and actively (for short-term measurements) in several ways by detecting alpha particles. **(Bayrak et al., 2013; Elísio & Peralta, 2020; Gutiérrez et al., 2004; Sofia Clareu Elísio & Luís Peralta, 2019)**

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1. Passive: e.g., solid state nuclear track detectors (SSNTD),
2. active e.g.:
   - with a semiconductor Si photodiode / Si semiconductor surface barrier detector,
   - pulse ionization chamber,
   - electrostatic charge accumulation,
   - Lucas scintillation cells.

Activity concentration of Rn can be expressed through the mass balance law of conservation of mass in the system. For the Rn component, this can be represented by the mass balance in **Equations 1 and 2** as follows **(Park, Kang, & Kim, 2016):**

$$N_{\Sigma Rn} = N_{Rn\_in} - N_{Rn\_out} - N_{Rn\_decay} \quad (1)$$

where are:
$N_{\Sigma Rn}$ - total number of Rn atoms in observed volume of space
N_{Rn_in} - number of inflow/entry Rn atoms into space
N_{Rn_out} - number of outflow/removal Rn atoms out from space
N_{Rn_decay} - number of decayed Rn atoms in space

$$\frac{\Delta C_{Rn}}{\Delta t} = \frac{F \cdot S}{V} - \lambda_{Rn} \cdot C_{Rn} \quad (2)$$

where are:
ΔC_{Rn} - change in concentration/rate of accumulation of Rn ($Bq \cdot m^{-3}$)
F - total Rn density flow/flux in enclosed space per unit surface ($Bq \cdot m^{-2} \cdot s^{-1}$)
S - total effective surface of radon flux (m^2)
V - observed volume of enclosed space (m^3)
λ_{Rn} - decay rate of Rn (s^{-1})
Inflow/entry is process of migration of Rn into building and and outflow/removal is ventilation of the building/enclosed space, and in a stationary state, there is no change in concentration ($\Delta C_{\Sigma Rn} = 0$).

Goal of this presentation is to show results of some Rn measurements indoor and in mines with different instruments, which are conducted to develop model which aims to reduce the number and time of measurements needed to determine the long-term level of active concentration and to improve and innovate at least one part of the existing research that deals with determining and predicting changes in the indoor active concentration of Rn (buildings and mines**). (Groves-Kirkby et al., 2006; Janik et al., 2012; Mphaga et al., 2024; Nunes & Curado, 2023)**

Several measurements were perfomed in lab, faculty indoor premises and mines using comercially available instruments with features and parameters shown in Table 1.:

Table 1. Rn concentration measurement instruments.

DEVICE MODEL:	1. Bertin AlphaE	2. RadonEye RD200	3. Sarad Home Scout	4. Radonova Robin² sensor
Application	indoor (low concentration in buildings), outdoor (underground environment)	Internal, short-term	long-term monitoring of radon indoors, concentration in the air (homes)	Indoor and outdoor (underground environment)
Duration of measurement	Long-term, short-term, continuous	short-term, continuous	Long term	Long-term, short-term, continuous (converts concentration into proportional output analog voltage signal)
Detection Mode	Silicon Semiconductor Diode Diffusion Chamber	Dual pulsed ionization chamber	Semiconductor Silicon Detector	Filtered diffusion in high-voltage Comoros - alpha spectrometry
MEASUREMENT RANGE (Bq/m³)	20 – $10 \cdot 10^6$ (10 MBq/m³)	7 – 3,700	1 … $1 \cdot 10^6$ (1 MBq/m³)	0-4000

One of the results from the lab measurements with different instruments is presented in **Figure 1**. The measurement was performed in a 10 liter sealed box with a radium/radon emission source, without ventilation inside the box.

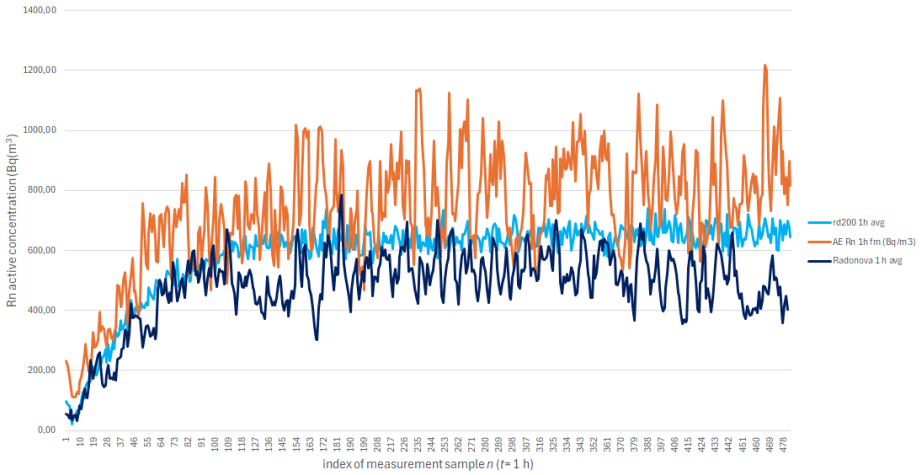

Figure 1. Time series graph of comparison of measurements with different instruments in enclosed box 10 lit. volume.

One of the results of faculty building room measurements are presented in **Figure 2**. This measurement used only one instrument and showed effects of low and higher rate of ventilation (higher rate of ventilation was partially opened window):

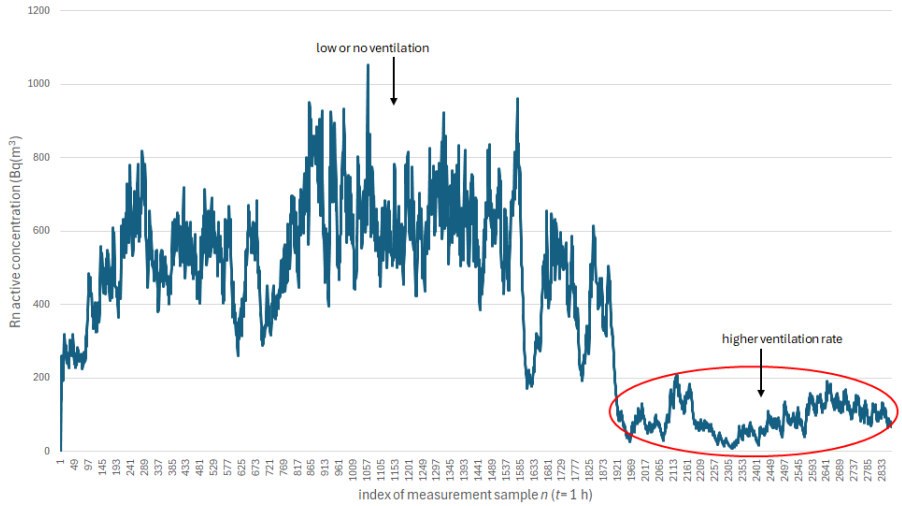

Figure 2. Time series graph of faculty building room measurements with low and higer rate of ventilation

Results of measurements inside Sv. Barbara mine, Samobor, Croatia with Bertin AlphaE is presented in **Figure 3**:

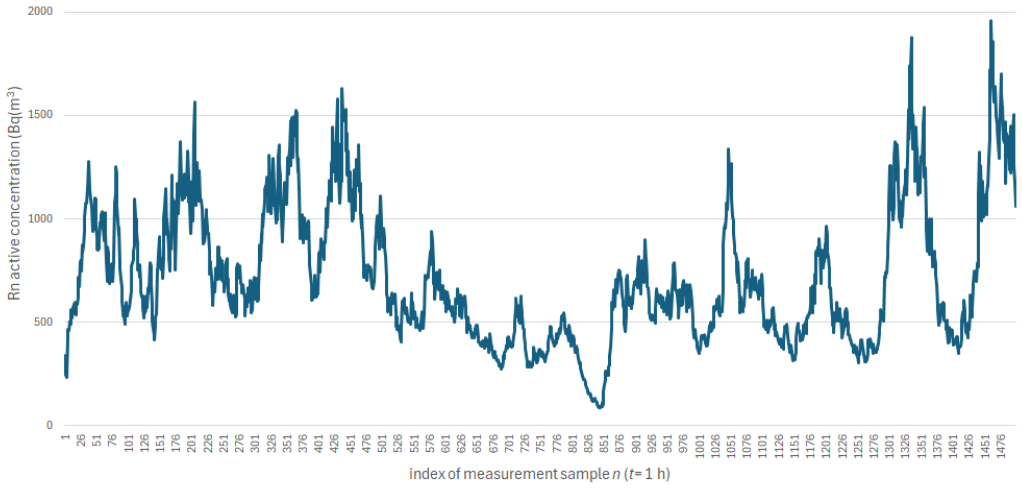

Figure 3. Time series graph of measurement inside mine corridor.

Preliminary research results:

• Measurements have shown that the concentration of Rn remains within limits that encompass the average measurement over a time period measured in days, weeks, or months and that it shows a strong correlation with changes in pressure and precipitation (rain).

• Due to higher time resolution, significant measurement unreliability and large range of concentration changes, measurements are conducted over an extended period (weeks and months or an entire year at the same/single location) and individual measurements are averaged into a variable mean (eng. floating average/mean) over a period of 1 hour or 4 hours.

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Author's contribution

Hrvoje Vukošić (assistant): conceptualization, data curation, formal analysis, investigation, writing – original draft, **Željko Ban** (professor): supervision, conceptualization, writing – review & editing, **Dalibor Kuhinek** (professor): supervision, conceptualization, methodology, writing – review & editing, **Želimir Veinović** (assistan professor): supervision, conceptualization, writing – review & editing.

All authors have read and agreed to the published version of the abstract.

Analysis of Drilling Parameters for Construction Pit Excavation

DIM-ESEE Conference
15th – 17th October 2025, Dubrovnik, Croatia

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Oral	Poster	No preference
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Presenting author: Siniša Stanković

Keywords: drilling, construction pit, excavation, predictor equation.

Abstract

Drilling accuracy and geometry govern blasting outcomes in construction pits where perimeter control and vibration limits are strict. This study proposes a simple predictor that links drill pattern geometry to borehole diameter, allowing rapid first-pass design without explicitly specifying explosive type and quantity. A dataset from Croatian construction pits (Povlja, TC Koromačno, Kvarner Palace–Crikvenica, Dubrovnik, Vis, Visoka–Split) was cleaned using a two-sigma outlier rule and de-duplication, minimum/maximum depths were combined and depth normalized to 1 m in line with common powder-factor practice. For each blast, the burden–spacing product (Bs, m²) and borehole diameter (Φ, mm) were extracted. Linear regression yielded the predictor $Bs = 0.0825 \cdot \Phi - 2.4859$ with $R^2 = 0.7598$ (n = 7 unique Φ–Bs pairs). Validation against measured Bs showed good agreement for most cases: five of seven predictions were within 0.78–1.10× of measured values, with two outliers (Φ = 52 mm and 32 mm) at 3.68× and 0.31×, respectively. The equation provides a transparent estimate of Bs that can be split into burden and spacing using customary B:s = 1:1 to 1:2 ratios, helping to seed designs for urban construction pits where drill quality and wall control dominate performance. While site-specific calibration, monitoring, and powder-factor adjustment remain essential, the predictor offers a practical starting point that can shorten early design cycles and support the selection of drill diameter and pattern within excavation constraints.

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Blast Vibration Optimization at a Limestone Quarry by Using E*STAR Electronic Detonators and Advanced Modelling Methods

DIM-ESEE Conference
15th – 17th October 2025, Dubrovnik, Croatia

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	X

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X		

Presenting author: Enes Kubat

Keywords: Electronic Detonator, Blast Optimization, Ground Vibrations, Blasting Software

Abstract

This paper presents a modern blasting approach based on a combination of advanced software technologies and E*STAR electronic detonators. The future of blasting should be built on sustainable and environmental-friendly use of civil explosives, detonators, and blasting equipment.
A unique geomorphological phenomenon, historical Koneprusy caves, are situated in Central Bohemia, 40 km from Prague, Czech Republic and in close proximity of one of the biggest quarries in Czech Republic, Certovy Schody. To protect the historical caves and their ecosystems, the ground vibration limits for blasting was set and the stationary vibration monitoring devices were placed inside the caves. Non-electric detonators were used but vibration results were unpredictable due to slight timing inaccuracies, fixed delay times and no vibration analysis. Quarry decided to try electronic detonators.
The innovative blast optimization software is used to achieve vibration goals as well as to keep the production balance. Since that time, every single blast is analyzed to the details, and optimum solution for PPV a PVS is chosen. Among the major advantages of a complete process was the accuracy and timing variability of E*STAR detonators.
Results: After the completed transition to electronic detonators, the achieved results were more than satisfying. Blast vibrations are reduced by 14% even with the explosive amount by delay interval is increased by 100%. Afterward, constant vibration results empowered us to increase the blast size as well. Up to now, with multi-decking and multi-rows, the total blast size has been increased by 300%. In this particular case, the power of technology has shown incredible results, and that is the path we would like to follow.

Author's contribution

Enes Kubat (Bc. Ing): conceptualization, methodology, testing, data analysis, original draft and writing, **Vojtech Kala** (Ing. Ph.D.): conceptualization, methodology, testing, data analysis, original draft and writing.

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VOT3D Project – New experience in optimizing ventilation in underground mines

DIM-ESEE Conference
15th – 17th October 2025, Dubrovnik, Croatia

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Presenting author: Adam Wróblewski

Keywords: laser scanning, excavation geometry modeling, numerical air flow modeling, mine ventilation optimization

Abstract

Ventilation of underground excavations in deep mines means supplying fresh air and diluting harmful gases in the workplaces of miners. When a room-and-pillar system is applied, it is necessary to provide relatively large amounts of air, which is a challenge in technical and economic terms.

Thanks to financial support from EIT Raw Materials, an international consortium of leading specialists in the field is researching the possibilities of optimizing mine ventilation by developing corridors geometry models and airflow modeling. As part of the project, the application of various laser scanning technologies (terrestrial, mobile, aerial - drones) and modeling the geometry of large-scale objects was verified. An original measurement system was developed for spatial data acquisition, together with its processing methodology. A data-driven construction method for geometric models is proposed for subsequent modeling and analysis of air flow using CFD tools, considering the real shape of the ventilation network. Based on the model analysis, the possibility of reducing the local drag coefficient and, consequently, reducing the costs of ventilation, was demonstrated.

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Prediction of the stability of mining excavation using numerical methods in Polish copper ore mines located at different depths

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Oral	Poster	No preference
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Presenting author: Daniel Pawelus

Keywords: finite element method (FEM), numerical simulations, stability of access excavations, Polish copper ore mines

Abstract

The regulations on the selection of roof support systems for the headings and production excavations in the Polish copper ore mines (the Lubin mine, the Polkowice-Sieroszowice mine, the Rudna mine) do not allow for the values of primary stresses in the rock mass at the depth of the excavations **(Collaborative Publication (2017)**. As a result, the roof support system may be inappropriately selected and lead to problems with the stability and functionality of the excavations. This fact may be of particular importance in the case of headings (both access and preparatory excavations) which have transport or ventilation functions. Numerical methods have significantly expanded research possibilities related to the analysis and evaluation of the stability of excavations in underground mines. They are used to solve problems related to driving excavations in underground mines in difficult geological and mining conditions **(Adach-Pawelus & Pawelus, 2021; Batugin et al., 2021; Adach-Pawelus, 2022; Kruszewski et al., 2022; Wang et al., 2022; Tahmasebinia et al., 2023; Tahmasebinia et al., 2023)**. The presented results of numerical simulations are a continuation of research on the stability of mining excavations in the Polish copper ore mines, which was briefly described in the publication "*Numerical methods as an aid in the selection of roof bolting systems for access excavations located at different depths in the LGCB mines*" **(Pawelus & Butra, 2024)**.

The Rudna mine was selected for numerical analyses. The decrease or the loss of stability in headings located at different depths (1000 m b.g.l. and 1250 m b.g.l.; "b.g.l." = below ground level) in the Rudna mine were modelled with the use of numerical simulations. The numerical calculations were performed in the Phase2 v.8.0 software, which is based on the finite element method (FEM). Numerical analyses were performed for a group of two headings. The excavations have a trapezoidal shape. In the headings, the side walls were inclined at an angle of 10°. The headings were protected with full-length-grouted rockbolts (RM-18 1.8 m long bolts) in a 1.5 m × 1.5 m bolting grid. The adjacent excavations are separated by pillars 20 m in width. **Table 1** lists the dimensions of headings in their assumed cross-sections.

Table 1. Dimensions of the analysed headings from the Rudna mine.

Excavation height	Excavation width below the roof	Excavation width at the floor	Mean excavation width	Excavation surface area
3.50	7.00	5.80	6.40	22.40

The stress values were identified from the R-XI shaft profile as per PN-G-05016:1997 **(Polish Standard PN-G-05016:1997)**. The calculations included the porosity and water-logging of the rock layers. **Table 2** shows the calculated primary stress values for two heading depths: 1000 m b.g.l. and 1250 m b.g.l. Owing to the deposit depth, the hydrostatic state of stress was assumed in the numerical models.

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Table 2. Primary stresses for two depths in the Rudna mine

Depth H [m]	Vertical stresses σ_z [MPa]	Horizontal stresses σ_x [m]	Horizontal stresses σ_y [m]
1000	19.02	19.02	19.02
1250	25.78	25.78	25.78

Two variants of loads acting on the group of headings were assumed for the numerical calculations. The flat, rectangular plate with openings shaped to correspond to the shapes of the analysed excavations located inside was assumed to be loaded on its edges:

- Load variant 1 (heading depth H = 1000 m b.g.l.):
  - side edges: p_x = 19.02 MPa,
  - upper edge and bottom edge: p_z = 19.02 MPa,
  - direction perpendicular to plate surface: p_y = 19.02 MPa.
- Load variant 2 (heading depth H = 1250 m b.g.l.):
  - side edges: p_x = 25.78 MPa,
  - upper edge and bottom edge: p_z = 25.78 MPa,
  - direction perpendicular to plate surface: p_y = 25.78 MPa.

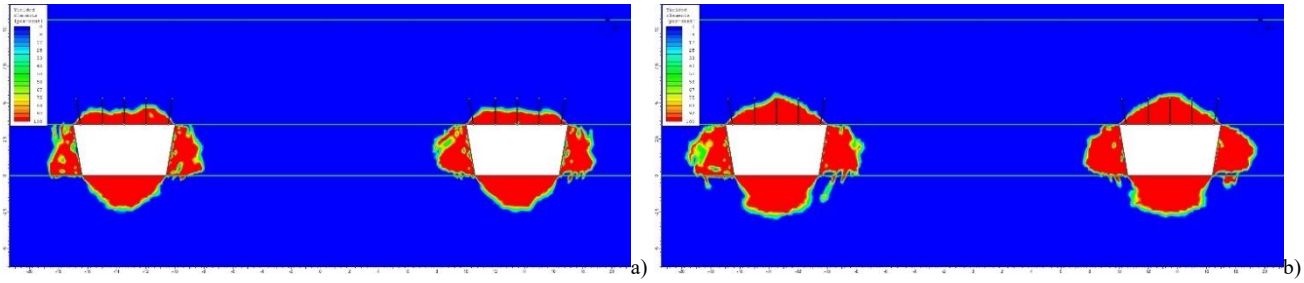
Numerical analyses were performed for an isotropic and for a uniform medium. The RocLab 1.0 software and Hoek - Brown classification **(Hoek, 1994; Hoek & Brown, 1997; Hoek & Marinos, 2000; Hoek et al., 2002)** were used to determine the rock mass parameters (strength and strain parameters). The rock medium was described with the elastic-plastic model with softening (layers in the roof and walls) and with the elastic-plastic model (layers in the floor). **Table 3** shows the strength and strain parameters of the rocks in the model. The numerical model was developed on the basis of the Mohr - Coulomb failure criterion.

Table 3. Rock mass parameters adopted for the numerical modelling **(Pawelus & Butra, 2024)**

Location	Rock Type	h [m]	E_s [MPa]	ν [-]	σ_t [MPa]	φ [°]	c [MPa]	δ [°]	φ_{res} [°]	c_{res} [MPa]
Roof	Anhydrite I-III	5.50	29,356.00	0.24	0.871	38.66	8.137	2.00	36.73	1.627
	Anhydrite IV	9.30	28,066.78	0.24	0.696	38.66	6.505	2.00	36.73	1.301
	Dolomite I-VIII	7.20	52,975.30	0.25	3.611	39.00	14.879	2.00	37.05	2.976
Walls	Dolomite - shale - sandstone formations	3.50	17,435.35	0.20	0.976	37.41	5.971	2.00	35.54	1.194
Floor	Sandstone	9.50	7072.00	0.14	0.093	39.06	2.520	2.00	39.06	2.520

The symbols used in the above table are as follows: h - thickness of rock layers, E_s - longitudinal modulus of elasticity, ν - Poisson's ratio, σ_t - tensile strength of the rock mass, φ - internal friction angle, c - cohesion coefficient, δ - dilatancy angle, ϕ_{res} - residual internal friction angle, c_{res} - residual cohesion coefficient.

Underground observations in Polish copper ore mines confirm the obtained results of numerical modeling of the stability of excavations located at different depths in the rock mass (1000 m below ground level and 1250 m below ground level) in the geological and mining conditions adopted for the Rudna mine. The maximum range of the yielded rock mass (from 50 % to 100 %) in the roof (**Table 4**) of the headings located at the depth of 1000 m b.g.l. (load variant 1) was from 1.09 m to 1.25 m (**Figure 1a**). For comparison, the maximum range of the yielded rock mass (from 50 % to 100 %) in the roof of the headings located at the depth of 1250 m b.g.l. (load variant 2) was from 2.03 m to 2.05 m (**Figure 1b**). A change in the heading depth from 1000 m b.g.l. to 1250 m b.g.l. has thus caused the range of the yielded rock mass in the heading roof to increase from 0.78 m (heading 1) to 0.96 m (heading 2). The maximum range of the yielded rock mass in the roofs of all headings (heading 2) was greater than the 1.8 m range of the bolted zone. This fact indicates that in the Polish copper ore mines, the heading depth in the rock mass may have a decisive impact on its stability. Problems with heading stability may occur when the yielded rock zone in the roof is larger than the bolted zone.



a) b)

Figure 1. Yielded element area around headings 1 and 2: a) Load variant 1, b) Load variant 2

Table 4. Yielded rock mass range in the roofs of the analysed excavations (yield between 50 % and 100 %)

Excavation	Yield range in the roof [m]		Increase in yield range in the roof	
	Load variant 1	Load variant 2	[m]	[%]
1	1.25	2.03	0.78	62.40
2	1.09	2.05	0.96	88.07

The numerical simulations allowed an optimal selection of the roof bolting design for headings driven at different depths in the rock mass in the conditions of the Rudna mine. For safety reasons, the simulations were based on an assumption that the bolted zone in the roof must be larger by at least 0.25 m than the maximum range of the yielded zone (yield from 50 % to 100 %). In the case of excavations conducted at a depth of 1000 m below ground level, RM-18 injection anchors with a length of at least 1.5 m in a grid of 1.5 m × 1.5 m (anchor spacing) should be selected. However, in the case of headings driven at 1250 m b.g.l., the range of the bolting zone should be increased. The selected bolts were at least 2.3 m long RM-18 grouted bolts in the 1.5 m × 1.5 m grid (bolt distance).

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Author's contribution

Daniel Pawelus (PhD, Eng.): conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, software, supervision, validation, visualization, writing – original draft and writing – review & editing.

Review of the mining methods for NRE-suitable deposits

DIM-ESEE Conference
15th – 17th October 2025, Dubrovnik, Croatia

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Presenting author: Vječislav Bohanek

Keywords: Platinum Group Metals, Narrow Reef Mining, Mechanized Mining, Room and Pillar, Breast Mining.

Abstract

Platinum group metals (PGMs) are a family of six chemically and structurally related elements used for industrial, medical, and electronic applications. Annual global production is estimated at 450–460 metric tons, with South Africa and Russia contributing nearly 80% of total supply. The Bushveld Complex in South Africa hosts the world's largest PGM resources, including the Merensky Reef, UG2 chromitite reef and the Platreef.

Traditionally, underground narrow reef mining of PGE metals is done by conventional drill and blast methods, but in the past two decades there has been a growing shift towards mechanization. The key drivers of this transition are higher productivity, improved safety, and reduced reliance on low-skilled labor **(Musingwini, 2010; Fourie et al., 2017)**. Mechanized methods are broadly divided into mechanical reef cutting and mechanized drill and blast. Mechanical reef cutting eliminates reentry delays and enables continuous operation, as demonstrated by Sandvik's Reef Miner MN220/MN330, Epiroc's Mobile Miner 22H, and Herrenknecht's Reef Boring Machine (RBM), which adapt tunneling and boring concepts to narrow reef mining **(Van den Berg, 2014; Vogt, 2016; Sifferlinger, 2022).** These technologies promise improvements in ore recovery, efficiency, and worker safety while reducing dilution and exposure to hazardous environments. Mechanized drill and blast method use low-profile (LP), extra-low-profile (XLP), and ultra-low-profile (ULP) equipment, adapted to different depths, dips, and geological conditions **(Fourie et al., 2017).** LP technology is suited for shallow operations with moderate complexity, while XLP and ULP equipment enable higher selectivity and improved ore quality at greater depths, though they require higher investment, complex infrastructure, and a highly skilled workforce **(Pickering & Leon, 2008; Andrews & Pickering, 2010).** The Narrow Reef Equipment (NRE) fleet, consisting of the Dozer, Drill Rig, and Support Rig, is battery powered and remote-controlled, designed for ultra-low profiles of 0.9 m to1.7 m. It improves safety, lowers emissions, and raises efficiency, with promising results obtained in trial testing. **(Bohanek et al., 2023)** While these advancements show significant potential, challenges remain regarding economic costs, orebody variability, and complexity of implementation. The future of PGM mining will depend on balancing geological constraints with technological adaptability, ensuring sustainable and profitable exploitation of these critical resources **(Vogt, 2016).**

The paper presents a comprehensive review of mining methods for deposits suitable for Narrow Reef Equipment (NRE), highlighting current practices and technological innovations.

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Author's contribution

Vječislav Bohanek (Assoc. Prof.): conceptualization and writing.

Detailed assessment of inorganic fouling content and heterogeneity of activated carbon in CIP/CIL circuits to optimize regeneration strategies and improve gold recovery

DIM-ESEE Conference
15th – 17th October 2025, Dubrovnik, Croatia

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Presenting author: Benedict Lazar

Keywords: Automated mineralogy, activated carbon, inorganic fouling, CIL/CIP, gold recovery

Abstract

Gold recovery from low-grade ores relies predominantly on cyanidation followed by adsorption onto granular activated carbon (GAC) (Fleming et al., 2011)). However, inorganic fouling of GAC is believed to significantly reduce its gold adsorption capabilities and, consequently, process efficiency (Macrae et al., 1988; Smith et al., 1984).

This study presents a methodology to characterize inorganic fouling on GAC used in carbon-in-pulp/carbon-in-leach circuits. A systematic protocol was developed to identify, quantify and map inorganic contaminant phases on GAC at the microscale using scanning electron microscopy-based automated mineralogy (**Figure 1**).

This approach enables detailed assessment of inorganic fouling content and heterogeneity, while also providing crucial insights into its development and state. Furthermore, it allows for site-specific optimization of GAC regeneration strategies, promoting more sustainable resource use and ultimately contributing to improved gold recovery.

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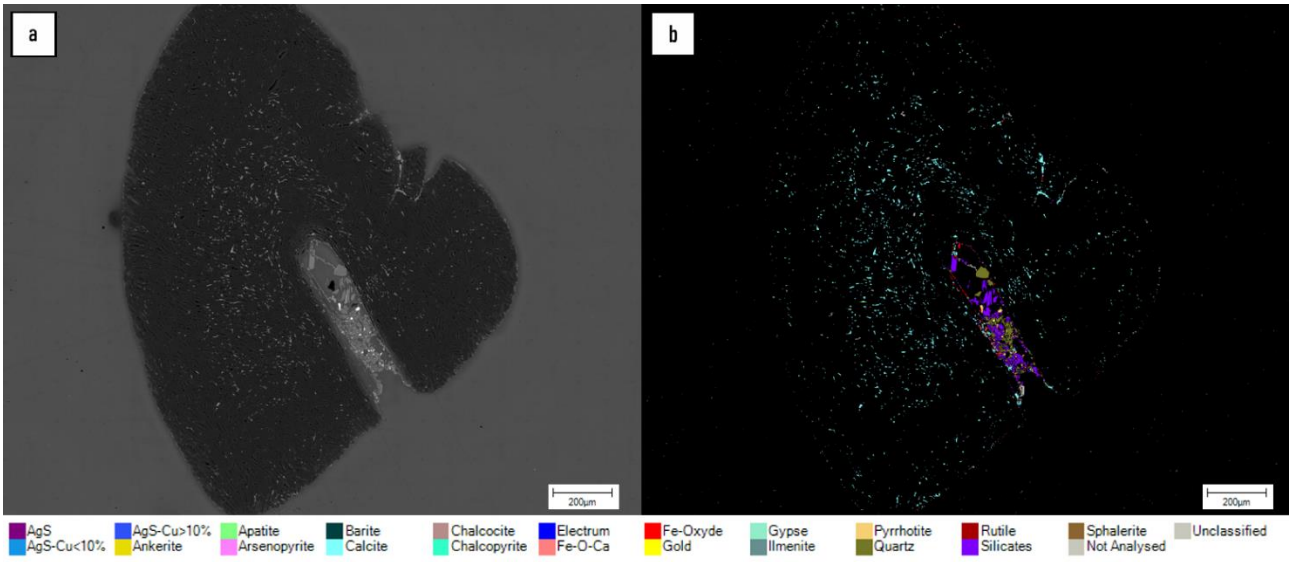

Figure 1. Backscattered electron (a) and false-color mineral classification (b) images of an activated carbon particle fouled with inorganic contaminants.

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Author's contribution

Benedict Lazar(MSc): investigation, methodology, data curation, formal analysis, visualization, writing – original draft. **Hassan Bouzahzah** (Dr.): conceptualization, supervision, methodology, validation, writing – review & editing. **Raphaël Mermillod-Blondin** (Dr.): resources, investigation, supervision, validation, writing – review & editing. **Eric Pirard** (Prof.): project administration, supervision, funding acquisition, writing – review & editing.

All authors have read and agreed to the published version of the abstract.

X = conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, software, supervision, validation, visualization, writing – original draft and writing – review & editing.

Circular Economy In Mining (Andraž Quarry)

DIM-ESEE Conference
15th – 17th October 2025, Dubrovnik, Croatia

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Presenting author: Lana Šteko

Keywords: "circular economy", "sustainable development", "metallurgical waste recycling", "legislative challenges", "industrial symbiosis"

Abstract

The transition from a linear to a circular economy is becoming a cornerstone of sustainable development in resource-intensive industries. This paper presents the case study of Andraž Quarry and Štore Steel in Slovenia, highlighting 15 years of practical implementation of circular economy principles in mining, metallurgy and construction. The approach integrates innovative technologies and cross-sectoral collaboration to transform metallurgical and construction waste into valuable secondary raw materials. Central to this initiative is the SWIM (Sustainable Waste Industry Management) project, which has enabled the development of new construction products, advanced recycling technologies, and environmental restoration strategies.

However, the process faced significant challenges, including legislative barriers, complex spatial planning procedures, high initial investment costs, and market resistance to recycled materials. Despite these obstacles, the Andraž Quarry and its partners have demonstrated that circular solutions can deliver ecological, economic, and social benefits when supported by systemic changes in policy, infrastructure investment, and public awareness. This case underscores the need for stronger cooperation between industry, government, and research institutions to fully realize the potential of circular economy models.

The Andraž Quarry and Štore Steel collaboration represents a leading example of circular economy implementation in Slovenia. Since the late 1990s, these companies have adopted practices that transform waste into resources, focusing on reusing metallurgical slag and construction debris as secondary raw materials for the construction sector. Through projects like SWIM, they have developed innovative technologies such as mobile modular machines (HEFAJST) for processing industrial waste, special concrete mixes, and asphalt solutions, which have been successfully applied in infrastructure projects.

The initiative has led to significant environmental benefits, such as reduced landfill use, lower greenhouse gas emissions, and conservation of natural resources. Additionally, it has fostered economic resilience by creating jobs and boosting regional competitiveness. However, widespread adoption of these practices has been hampered by regulatory fragmentation, slow permitting processes, high implementation costs, and societal skepticism toward recycled products.

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The case study highlights that achieving a functional circular economy requires not only technological innovation but also legal reforms, investment incentives, and multi-stakeholder collaboration. Moving forward, aligning governmental, industrial, and societal efforts is crucial to overcome systemic barriers and scale up sustainable practices across industries.

LCA of electric, remote control and automatic narrow reef mining equipment

DIM-ESEE Conference
15th – 17th October 2025, Dubrovnik, Croatia

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Presenting author: Davor Kvočka

Keywords: Life Cycle Assessment (LCA), platinum-group metals, extra low profile (XLP), narrow reef mining.

Abstract

The platinum group metals (PGMs) (i.e. Pt, Pd, Ru, Rt, Ir, Os) occur jointly in nature due to their similar physical and chemical properties. PGMs are often located in narrow and ultra-low-profile reefs, with extraction of PGMs from low-grade, thin and sub-horizontal reefs presenting both operational and environmental challenges. The extraction of PGMs particularly relies on specialized equipment capable of functioning within confined spaces and with minimal environmental impact. However, conventional underground mining techniques with existing equipment are energy-intensive and labour-demanding, thus resulting in high dilution, poor ore recovery and high environmental footprints.

The limited performance of classical mining technologies has led to the development of Low Profile (LP) and Extra Low Profile (XLP) equipment in order to increase the efficiency and improve environmental performance. Life Cycle Assessment (LCA) offers a systematic approach to evaluating the environmental impacts of mining technologies across their entire lifecycle, i.e. from equipment manufacturing through operation and eventual decommissioning. This study presents LCA of remote-controlled, electric-powered and automated narrow reef mining equipment (i.e. Electra-NRE equipment) tailored for PGMs extraction from low reef environments. LCA study quantifies energy consumption, greenhouse gas (GHG) emissions, material usage and waste generation for Electra-NRE equipment in comparison to conventional mining technology.

The preliminary results suggest that material and energy consumption during the production and operation of mining machinery are primary contributors to the overall environmental impact. The electric and automated equipment exhibits higher embodied energy during the production stage due to the specialised design, batteries and control systems. However, the use phase of electric and automated equipment leads to environmental benefit due to the reduced energy use per unit ore mined, lower dilution rates and reduced waste generation. Furthermore, remotely-controlled, electrically-powered and automated operation also reduces health and safety risks, thus improving working conditions in hazardous and confined underground environments. The preliminary findings highlight that electric and automated mining equipment can play an important role in improving the environmental performance of PGMs mining in narrow reefs.

Funding

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Red mud as geotechnical composite

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Keywords: red mud, recycling, geotechnical composites, environment.

Abstract

Most conventional methods of disposing of Red mud (RM), which is an extractive waste from the Bayer process, such as settling ponds or dry storage, pose significant environmental risks. This is primarily due to RM's high alkalinity and the potential leaching of hazardous elements (PTEs). Several efforts have been made to utilize RM as an additive in soil remediation or in the production of construction materials. However, due to its fine-grained texture, poor mechanical properties, and tendency to leach harmful substances, RM alone is unsuitable for direct use in construction. However, its mechanical properties and workability can be significantly improved by mixing it with hydraulic or pozzolanic binders, such as calcareous ashes.

In the present study, the influence of two different types of alternative recycled material, paper mill ash (PA), containing (latent) hydraulically active phases, on the geomechanical and environmental properties of geotechnical RM/PA composites are investigated. The results demonstrate that mixing PA with RM slurry produces a soil-like composite with suitable workability and mechanical properties for use in earthworks, such as embankments. These geocomposites exhibit geotechnical characteristics that, in some cases, surpass those of natural construction materials like silt or gravel. Moreover, the use of PA significantly reduces the leaching of potentially hazardous substances from RM, enhancing the environmental safety of the resulting composite.

This study confirms that red mud (RM), when stabilized with paper mill ash (PA), can be converted into a viable construction material. The resulting composites not only meet the geotechnical performance requirements for earthworks but also comply with environmental standards set by Slovenian legislation. This approach offers a dual benefit: it reduces the environmental burden associated with RM disposal while simultaneously decreasing the demand for natural construction materials.

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Geotechnical Behavior of Contaminated Clay Soils: A Microstructural and Plasticity-Based Assessment for Sustainable Soil Reuse

DIM-ESEE Conference
15th – 17th October 2025, Dubrovnik, Croatia

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Presenting author: Noémi Szász

Keywords: Atterberg limits, contamination, geotechnics, SEM, sustainability.

Abstract

Anthropogenic soil contamination in clay soils presents unique environmental challenges due to the distinct physical and chemical characteristics of these soils. Clay soils, characterized by their fine particle size and low permeability, tend to adsorb and retain a wide range of contaminants, including heavy metals, organic substances, and excess nutrients. (**Calabrese et al., 2005, Fang and Daniels, 2006, Pascucci, 2011**). While these properties can limit the mobility and leaching of contaminants, they also contribute to their long-term persistence and accumulation near the soil surface. Investigating these contaminants and understanding the changes they induce are essential for the effective implementation of both short- and long-term soil-related strategies outlined by the European Union. (**EU Soil Strategy for 2030, European Green Deal**) Generating empirical data on how contaminants affect soil structure and stability is essential for understanding the broader implications of soil contamination. Such data help reveal how geotechnical degradation induced by various contaminants can compromise key engineering functions of soils, including bearing capacity, permeability, and overall stability. This knowledge is critical for establishing risk-based thresholds that guide the safe management and potential reuse of contaminated sites. In this context, identifying geotechnical performance limits under contamination conditions can be viewed as a fundamental aspect of protecting the "infrastructure support" function of soils, one of the core functions emphasized in European Union soil protection frameworks.
Soil reuse (e.g., using excavated or remediated soils in construction or backfilling) is a key principle under the **EU Circular Economy Action Plan** and is supported by several national strategies. However, the reuse of contaminated soils poses both environmental and geotechnical risks.

In this study, the focus was placed on evaluating changes in the Atterberg limits of various contaminated clayey soils, supported by Scanning Electron Microscope (SEM) imaging to interpret the microstructural alterations underlying the observed geotechnical behavior. While the present analysis emphasizes plasticity-related properties, it forms part of a broader research effort aimed at assessing additional key parameters, including water absorption capacity, consolidation behavior, and shear strength, to comprehensively understand the impact of contaminants on the engineering performance of clay soils. All measurements were performed in accordance with relevant European standards. The conclusions drawn from this study, supported by prior research and literature reviews, underscore key correlations and causal relationships between the observed geotechnical changes and the chemical as well as crystallographic characteristics of the samples.
This research aligns closely with current European policy frameworks, including the proposed Soil Directive and the EU Green Deal, which emphasize the remediation and sustainable reuse of contaminated land. However, the practical

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implementation of these strategies depends on a thorough understanding of how contamination affects the engineering properties of soils. Reuse feasibility cannot be determined solely based on contaminant concentration; it must also account for changes in geotechnical performance. By quantifying the effects of various contaminants on properties such as plasticity, structure, and consistency, this study contributes to the establishment of performance-based thresholds that support both environmental protection goals and effective materials management policies.

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Author’s contribution

Noémi Szász (PhD student) provided the raw materials preparation, performed the laboratory work, and presentation of the results. **Andrea Tóth** (Associate professor) provided the evaluation of the experimental results and presentation of the results.

Laboratory Investigation of Cement Kiln Dust (CKD) for Stabilization of Clay Soil from Cegléd, Hungary

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15th – 17th October 2025, Dubrovnik, Croatia

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Presenting author: Sirine Trabelsi

Keywords: Soil stabilization, cement kiln dust, waste materials, clay, laboratory testing.

Abstract

Soil stabilization plays a crucial role in construction projects by improving the engineering properties of soil, such as strength, durability, and load-bearing capacity (**Harichane et al., 2011; Al-Mukhtar et al., 2012).** Traditional stabilization technologies typically involve the use of conventional materials, such as cement and lime. However, as environmental awareness grows and we transition into the world of sustainable practices, awareness of using industrial waste materials has come to attention (**Arulrajah et al., 2014**). Waste materials are produced in several industrial processes, and they provide a way to not only be environmentally sustainable but also include cost-saving performance, and provide a solution towards waste disposal (**Harichane et al., 2011**).

By-products of the industry, such as cement kiln dust (CKD), fly ash, ground granulated blast furnace slag (GGBFS), or other by-products based on pozzolanic materials can improve soil properties and are being an integral part of many sustainable approaches for soil stabilization. By utilizing waste materials in stabilization, they can divert materials from the landfill, as well as limit the amount of greenhouse gases produced in the manufacturing of traditional binders (**Consoli et al., 2009**). Recent articles and studies have examined and reviewed the use of various industrial waste for soil stabilization techniques, which can provide useful references on the applicability and usage of these materials **(Alhassani et al., 2021; Basha et al., 2005; Arulrajah et al., 2014; Sariosseiri & Muhunthan, 2009; Consoli et al., 2009**).

The material used in this study consists of medium plasticity clay soil collected from a mine site located in Cegléd, Hungary, and Cement Kiln Dust (CKD), an industrial by-product obtained from Duna-Dráva Cement Kft. The clay soil was classified using Atterberg limits and particle size distribution (**ASTM D4318-17e1, 2017**), and CKD was characterized both by X-ray Fluorescence (XRF), as well as X-ray Diffraction (XRD) based on the pozzolanic nature of some oxides, i.e., (CaO, SiO_2, and Al_2O_3) (**Arulrajah et al., 2014**).

In geotechnical engineering, laboratory tests are a vital aspect of evaluating and predicting soil behavior under various circumstances. To evaluate the effect of CKD on medium clay engineering behavior, several geotechnical tests were completed for evaluation purposes. The research used a detailed geotechnical testing program, including Atterberg limits, particle size distribution, ring shear testing, and cone penetration resistance, to show that CKD improves the physical and the mechanical properties of clay. This improved performance results from pozzolanic and cementitious reactions of

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reactive oxides in CKD (CaO, SiO_2, Al_2O_3) with minerals in the soil to develop cementitious compounds that enhance the bonding and interlocking of the particles (**Harichane et al., 2011; Al-Mukhtar et al., 2012**).

The study aligns sustainable engineering goals by promoting the reuse of industrial by-products and lowering reliance on energy-intensive, greenhouse gas-emitting traditional binders like cement and lime (**Arulrajah et al., 2014; Basha et al., 2005; Kaniraj & Havanagi, 2001**). In addition, CKD tackles the environmental problem of disposing of solid waste, promoting waste valorization techniques and the circular economy (**Kumar et al., 2007**).

Finally, this research encourages broader acceptance of low-carbon, cost-effective alternatives in geotechnical engineering practice, while also providing useful information about the practical application of green stabilizing methods. The results show the potential to convert problematic soils into resilient ground layers using industrial wastes to stimulate strong and sustainable infrastructure development (**Sariosseiri & Muhunthan, 2009**).

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Author’s contribution

Sirine Trabelsi (Ph.D student): conceptualization, investigation, methodology, writing – original draft. **Andrea Tóth** (associate professor): supervision, resources, review & editing. **Tamás Kántor** (associate professor): supervision, resources, review & editing.

All authors have read and agreed to the published version of the abstract.

Towards Carbon Neutral Concrete Production: Mechanical Activation and Alkaline Content for Concrete Construction and Demolition Waste based Geopolymer Binder

DIM-ESEE Conference
15th – 17th October 2025, Dubrovnik, Croatia

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Presenting author: Cornelius Ngunjiri Ngandu

Keywords: construction and demolition waste, mechanical activation, alkaline, geopolymer binder

Abstract

Concrete is one of the major resource globally, however cement production results to significant CO_2 emission. Massive utilization of geopolymer concrete can result to reduction of cement hence sustainable carbon neutral concrete. There is need to up-cycle construction and demolition waste (CDW), to ensure performance and durability for concrete.

This study aims at evaluating the impact of concrete CDW mechanical activation (MA) and alkaline content for concrete CDW based geopolymer binder. Experiment for varying MA of the concrete CDW precursor, at constant 0.65 alkaline: precursor, the highest 7-day compressive strength was (17.5 $\pm$ 0.77) MPa, for the precursor's geometric specific surface area and pass 50 % particle size (X_{50}) in the ranges of 6871.5 cm^2/g and 13.4 µm respectively. Experiment for varying alkaline content, the highest compressive strength was attained at alkaline: precursor ratio of 0.45, with 7-day compressive strength of (26.57 $\pm$ 1.28) MPa. MA and the alkaline content had a major impact on the strength. The study recommends that modelling major parameters that influence concrete CDW based geopolymer binder for production of carbon neutral concrete.

Introduction

Concrete is among the major resources utilized globally. However, production of cement clinker is a energy intensive activity that results to significant amount of carbon emissions. Currently, with concerns on negative climatic change impact, there is an urgent need to produce more sustainable concrete products. Those sustainable materials must meet the technical requirements- structurally, physically, durability, consistency- and also proved benefits environmentally, economically and socially.

In order to boost circular economy, appropriate value addition in waste recovery is paramount. Effective grinding process of waste can optimize on their physical and chemical properties as secondary raw materials or in place of natural pozzolana, locally available raw material. Disintegration (grinding) is a common method for dispersed systems production **(Juhász & Opoczky, 1990)**.

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This study was conducted into 2 series including: 1) Evaluation of rheological and hardened properies for geopolymer binder with raw and mechanically activated concrete CDW; 2) Utilizing the optimum particle size (grinding duration) from series 1 and evaluation of 7-day compressive strength for geopolymer binder with varying amount of alkaline content.

Material and Method

Material

The raw concrete CDW was obtain from < 4 mm concrete waste from Hungary, after jaw crushing the larger portions, with particle size and distribution as shown in **Figure 1**, with a single modal particle size around 3 mm (3000 µm) and particle sizes passing 80 % (X_{80}) and 50 % (X_{50}) of 3004.7 µm and 1598.8 µm. The X-Ray fluorescence (XRF) chemical composition is presented in **Table 1**, highest oxide being SiO_2 at 53.24 %.

Alkaline solutions were used as the geopolymer binder activation agents included 10M NaOH and sodium silicate (SS). SS **(Wöllner GmbH & Co. KG)**, composition 64.2 % of H_2O, 27.5 % of SiO_2 and 8.3 % of N_2O **(Szabó et al., 2022).**

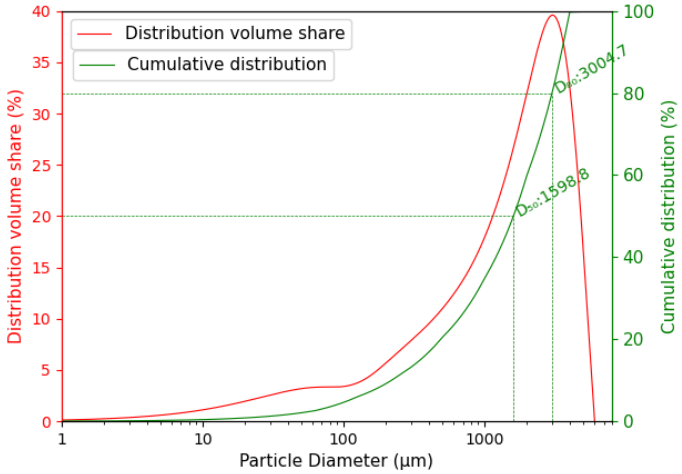

Figure 1. Distribution volume and Particle size distribution for raw concrete CDW.

Table 1. X-Ray fluorescence (XRF) Chemical composition for concrete CDW.

Content	SiO_2	Al_2O_3	MgO	CaO	Na_2O	K_2O	F_2O_3	LOI
% Mass	53.24	5.82	1.26	20.83	0.61	1.44	1.62	14.3

LOI: Loss of ignition

Method

MA for the raw concrete CDW was done in a plenatery mill. in a batched process. The mill has 4 bowl where the material and media are placed. Each bowl is Ø100 mm and 70 mm height at 150 mm radius to the centre of the bowl. The mill revolves at 128 revolutions per minute. The raw concrete CDW material was ground using 3 no., 40 mm steel balls media in each bowl, with a material to media ratio of 1:10 by mass. Duratons for grinding were 3, 5, 10, 15, 30, 60 and 120 minutes. The particle size distribution was taken for one or more batches using HORIBA® diffraction particle size analyzer for finer particles and sieving for coarser particles (lower grinding times), and the resultant was assumed corresponding representative particle sizes. A shape factor of 1.5 was suggested to compute the SSA estimated from spherical shape SSAs', also this aligned with **Maroof et al., (2020)** study.

Slumps was conducted with a mini-sump test, by measuring the flow diameters for the 1st series, using truncated cone mould with Ø 40 mm at the bottom. Diameter instead of the height of the mini-slump was measured, similar to **Kantro, (1980)** study.

All geopolymer binder specimens for compressive strengths were prepared by mixing concrete CDW precursor with alkaline solution including sodium silicate (SS) and 10M NaOH, in the mass ratio of SS:10M NaOH of 3:1. 20 mm cube molds were utilized, curing was conducted at 60 °C for 6 hours and 7-days compressive strengths were attained. The 1st series had alkaline to precursor ratio of 0.65, by mass with varying particle sizes and SSA's of concrete CDW and the 2nd series optimized the particle size and SSA's of concrete CDW with varying alkaline to precursor ratio of 0.45, 0.55, 0.65 and 0.75.

Results

Table 2 show the X_{50}, X_{80} and geometric SSA, for various grinding durations, attaining a minimum X_{50}, of 9.8 µm after 120 minutes and geometric specific surface areaof 11214 cm^2/g.

Table 2. Particle sizes at passing 50 % (X_{50}) and 80 % (X_{80}) and geometric SSA

Grinding time (min)	X_{50} (µm)	X_{80} (µm)	Specific surface area (cm^2/g)
3	213	468.3	153
5	161.9	378.3	225
10	83.6	262.4	2196
15	50.2	173.5	3042
30	18.5	64.6	5203
60	13.4	43.6	6872
120	9.8	37.9	11214

The slump reduced significantly with increasing geometric SSA. Figure 2, are the stengths and densities variation for series 1 and 2, optimum X_{50} (median particle size) in the range 13.4 µm, and optimum alkaline content (with fixed particle size at optimum, from series 2) at 0.45 alkaline to precursor content.

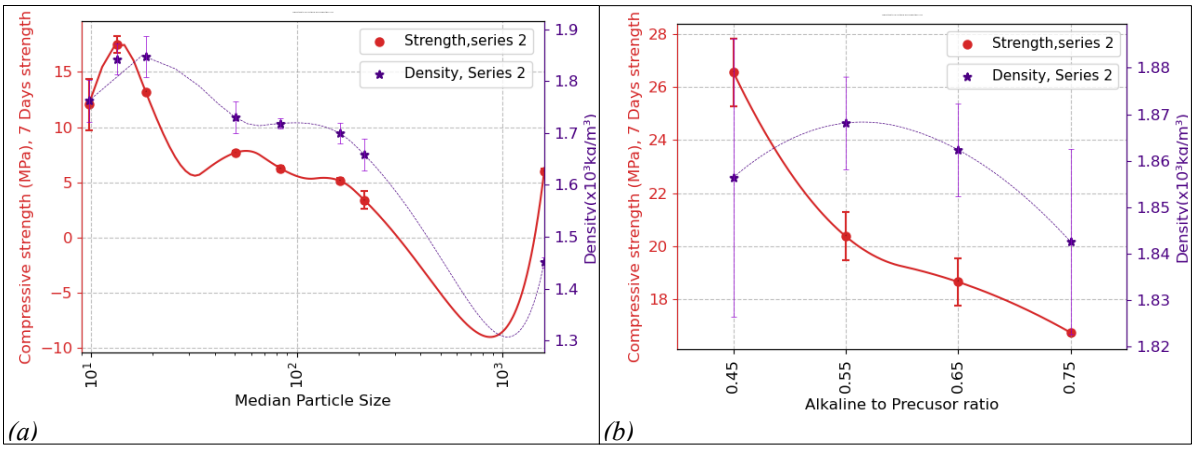

Figure 2. Compressive strengths and densities for: (a) Series 1, varying activation (b) Series 2, varying alkaline content

Discusion and Conclusions

Based on this study, mechanical activation and alkaline had a significant impact on the resultant geopolymer binder, and they can be optimized to improve the performance of geopolymer concrete. There is a need for modelling precursor particle size and alkaline content, with other important factors to accurately predict geopoymer concrete performance and durability hence promote the utilization of carbon-neutral concrete.

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Author's contribution

Cornelius Ngunjiri Ngandu: laboratory work and writing manuscript **Gábor Mucsi** (Professor): Leadership and Direction

All authors have read and agreed to the published version of the abstract.

Development of Porous Foam Glass from End-of-Life PV Panels Using Secondary Raw Materials

DIM-ESEE Conference
15th – 17th October 2025, Dubrovnik, Croatia

Busra Karakas[1*], Ildikó Fóris[2] , Gábor Mucsi[2],
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Presenting author: Ildikó Fóris

Keywords: PV panel, glass foam, recycling, secondary raw materials.

Abstract

The growing accumulation of end-of-life photovoltaic (PV) modules presents a critical environmental issue, particularly due to the substantial volume of non-biodegradable glass components. This study investigates recycling of PV panel glass waste into porous glass foam using thermal treatment methods, aiming to create lightweight, insulating materials suitable for heat inulation. The research focused on the effects of processing parameters and secondary raw material additives on foam quality, density and mechanical performance. Experiments were conducted using crushed PV panel glass powder (<100 µm) sourced from manually disassembled, post-consumer modules. Eggshell powder (1 wt %) was used as a foaming agent due to its calcium carbonate ($CaCO_3$) content, while red mud (5 wt %) and fly ash (5 wt %)—industrial waste products—were investigated as additional additives. Na-bentonite was added (2 wt%) as a binder. Specimens were formed into cylindrical pellets (10 g each) using a hydraulic piston press at 30 MPa.

Thermal treatment was performed in a Nabertherm static laboratory furnace across temperatures of 750 °C – 900 °C, at different heating rate and holding time. Physical properties, including density and volume expansion, were determined using the geometric method, while mechanical integrity was assessed by a standardized falling test. Microstructural changes and foaming efficiency were evaluated through comparative image analysis.

The lowest density (0.17 g/cm³) was achieved at 900 °C and 10 °C/min with red mud and eggshell powder. Increasing the foaming temperature and heating rate enhanced gas entrapment and porosity whereas extended holding times sometimes resulted in densification due to the escape of generated gases. Fly ash-containing samples exhibited limited foaming behavior and higher densities (>1.00 g/cm³), likely due to reduced viscosity control.

Mechanica resistance, as evaluated through repeated falling tests, showed no direct correlation with specimen density but was instead influenced by pore morphology and distribution. In contrast, slower heating rates and extended holding times led to thicker cell walls and structural heterogeneity, which adversely impacted the mechanical integrity of the foams.

The results confirm the practical potential of repurposing photovoltaic panel glass waste into lightweight, porous foam glass through the use of environmentally friendly additives. This research supports the broader adoption of secondary raw materials in circular economy models and contributes to lowering the environmental impact associated with both PV panel disposal and construction materials.

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Author's contribution

Busra Karakas (Master student) performed the laboratory work, and presentation of the results. **Ildikó Fóris** (PhD student) provided the raw materials preparation, performed the laboratory work, and presentation of the results. **Gábor Mucsi** (Professor) provided the evaluation of the experimental results and presentation of the results.

All authors have read and agreed to the published version of the abstract.

Mechanical Pretreatment of a Mild Hybrid Lithium-Ion Battery Pack – Recovery of Black Mass

DIM-ESEE Conference
15th – 17th October 2025, Dubrovnik, Croatia

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Presenting author: Tamás Kurusta

Keywords: lithium-ion batteries, mechanical processing, recycling, black mass.

Abstract

Lithium-ion batteries (LiBs) are an indispensable component of modern technologies, powering devices ranging from consumer electronics to electric vehicles and grid-scale energy storage systems. With the rapid growth in electric mobility, the accumulation of end-of-life (EoL) LiBs has become a pressing issue, posing both environmental hazards and resource recovery challenges. Their diverse structure and chemical composition make the handling, dismantling, and recycling of EoL batteries a particularly complex challenge. Mechanical preparation is the basis for all following hydrometallurgical or pyrometallurgical processes. Therefore, it is essential to plan and perform it correctly.

This study focuses on the mechanical dismantling and pretreatment of a lithium-ion battery pack extracted from a Ford Transit mild hybrid vehicle. The research aimed to recover valuable materials, especially black mass, which contains critical metals such as lithium, cobalt, and nickel, with mechanical operations.

The complete workflow included manual disassembly, cell discharge with a resistive load, mechanical opening using rotary shears, and thermal treatment at 60 °C for 48 hours to evaporate volatile electrolyte components. Following the thermal treatment, the battery cells were subjected to a two-stage size reduction using a hammer shredder with a 20 mm 8 mm sieve.

The resulting material was classified based on particle size, with the fraction smaller than 1 mm designated as black mass. ICP (Inductively Coupled Plasma) analysis revealed that the recovered black mass originated from an NMC-type battery and contained significant concentrations of nickel (17.3 wt %), cobalt (4.53 wt %), and lithium (3.39 wt %). The black mass recovery efficiency was approximately 74 wt %, with a purity exceeding 90 %, demonstrating the suitability of mechanical techniques for producing high-quality recyclable fractions.

Additional material recovery efforts focused on the 4 mm – 16 mm fractions, which predominantly contained aluminum and copper foil components, along with a minor black mass coating. These were enriched through air-flow separation, optimized at an air velocity of 2.68 m/s, which allowed for efficient separation of metallic and polymeric materials.

The outcomes of this research highlight the effectiveness of mechanical pretreatment in separating valuable fractions from spent LiBs with minimal environmental footprint and without the need for chemical reagents at this stage. It establishes a foundation for the development of closed-loop recycling systems and contributes to the sustainable management of critical raw materials.

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Author's contribution

Tamas Kurusta (1) (PhD student) provided the raw materials preparation, performed the laboratory work, and presentation of the results, **Sándor Márton Nagy** (2) (associate professor) provided the evaluation of the experimental results and presentation of the results

All authors have read and agreed to the published version of the abstract.

Substantiation of phytoremediation technology for soils contaminated by technogenic and military impacts in Nikopol district, Ukraine

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Presenting author: Oleksandr Kovrov

Keywords: phytoremediation, heavy metals, land reclamation, plants.

Abstract

Since the outbreak of Russia's full-scale war against Ukraine in February 2022, the Ukrainian environment has undergone catastrophic changes. Soil cover, the basis of agriculture, a source of food security, and a component of ecosystem stability, has suffered particularly significant losses. Military operations, the destruction of industrial facilities, explosions, fires, and the leakage of chemicals and oil products have caused serious soil pollution and degradation in large parts of Ukraine. The fertility of such soils is rapidly declining due to the destruction of the structure, loss of organic matter, destruction of microflora, and accumulation of toxicants.

Pollution is local, regional, and even transboundary, and its effects can last for decades.

According to the State Ecological Inspectorate, thousands of hectares have been found to have excessive levels of heavy metals and explosives. More than 30% of arable land in the combat zones has lost its fertility or needs reclamation. Studies by the National Academy of Agricultural Sciences show that complete soil restoration will take 10-20 years and require hundreds of millions of dollars. The United Nations estimates that the environmental damage caused to Ukrainian soils already exceeds $10 billion.

In this regard, it is relevant to apply scientifically based restoration methods that can restore agricultural potential to the affected territories to ensure food security and sustainable development of agriculture in Ukraine. In conditions of war and post-war restoration, it is important not only to know the available methods of reclamation but also to be able to correctly choose the method or their combination depending on the type of damage, soil properties, and available resources.

Phytoremediation technologies present the modern ecological strategy for the reclamation of degraded and contaminated lands, which are based on the ability of green plants to clean up soil, water, and air **(Kovrov et al., 2024; Salt et al., 1995).**

Currently, there are many positive results of using specific plant species for phytoremediation and restoration of biodiversity in man-made landscapes. The modern technologies for ecological revitalization and bioremediation of degraded lands have an emphasis on integrated biotechnological approaches with application of microorganisms **(Butu et al., 2021)**.

The article **(Adesodun et al., 2010; Rizwan et al., 2016)** presents a study of the phytoremediation potential of sunflowers *Tithonia diversifolia* and *Helianthus annuus* for the removal of zinc and lead from contaminated soils. The results showed the ability of both species to accumulate heavy metals in their above-ground parts, which indicates their

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effectiveness as phytoremediation plants. The authors emphasize the prospects for using these crops for the ecological cleaning of contaminated lands.

The phytoextraction and phytofixation of heavy metals from contaminated by various plant species is considered an effective natural mechanism that allows effective accumulation and limitation of heavy metals mobility in the soil environment **(Cheraghi et al., 2011).**

Different types of hyperaccumulator plants have different capacities concerning the extraction of heavy metals **(Padmavathiamma et al., 2007).** For example, *Brassica juncea L.* has an outstanding potential for the phytoremediation potential for the purification of soils contaminated with a wide range of heavy metals. The process of hyperaccumulation influences the physiological and biochemical mechanisms of the accumulation of toxicants and launches the adaptation of the plant to stressful conditions **(Rani et al., 2023).**

The accumulative potential of plants is widely used for water treatment technologies, for example the rhizofiltration, as the process of heavy metal uptake by plant root systems from the aquatic environment. In the paper () the authors present a mathematical approach to predict the dynamics of metal accumulation in roots depending on their concentration and biological parameters. The proposed model contributes to the optimization of the use of rhizofiltration as an effective technology for bioremediation of polluted waters **(Verma et al., 2006).**

Nevertheless, the application of phytoextraction as a tool for the purification of the environment from heavy metals has some limitations. Some factors affecting the efficiency of the process, in particular, the type of soil, properties of metals and plant species can significantly influence the restoration process especially for large-scale remediation needs **(Suman et al., 2018).**

This paper presents the study of the impact of military operations on the soil environment at the Nikopol district of Dnipropetrovsk region (Central Ukraine). Since the February 2022, this territory has been suffered from constant missile attacks from the temporarily occupied left bank of the Dnipro River, in particular from the territory of the Zaporizhia region. This choice is due to the high level of anthropogenic and technogenic load on the natural environment, the duration of the impact, and the significance of the area in the agricultural and ecological context. The Nikopol district has developed agricultural infrastructure with a predominance of black earth, chestnut, and meadow-black earth soils, which are the basis of agricultural production. Constant shelling by artillery, missiles, and drones has led to soil contamination with explosive residues, combustion products, fuels, lubricants, heavy metals, and toxic compounds; mechanical destruction of the structure of the arable layer; destruction of the humus horizon in some areas; increased erosion risks due to the destruction of vegetation cover.

Considering the agricultural significance of the territory and its potential for further economic use, the development of practical, scientifically based approaches to restoring fertility and environmental safety of the soils of the studied area is of particular relevance.

The purpose of the study is to develop and scientifically substantiate phytoremediation technology to reduce the content of heavy metals and nitrates in contaminated soils of the Nikopol district with the subsequent restoration of fertility and the possibility of safe land use.

The following tasks are set for this case-study:

- to analyze the ecological state of soils in areas of contamination as a result of military operations and flooding in the Nikopol district;
- to identify the main types of pollution and determine their impact on the agro-properties of soils;
- to substantiate the feasibility of using the phytoremediation method in specific conditions of the area;
- to select phytoextractor plants with high potential for the removal of specific pollutants, taking into account the local soil and climatic conditions of the region;
- develop a phased scheme for the application of phytoremediation, taking into account the local soil and climatic conditions of the region;
- substantiate agrotechnical measures to increase the efficiency of the phytoremediation process;
- assess the efficiency of soil purification using phytosorption according to the criteria of reducing pollutant concentrations and restoring soil bioactivity;
- calculate the economic feasibility of the proposed technology using the example of 1 ha of a contaminated site;
- provide practical recommendations for the implementation of phytoremediation technology for soil restoration on other contaminated sites.

The scientific novelty of the proposed technology lies in an integrated approach to the purification of soils contaminated with heavy metals and nitrates by combining the phytoremediation properties of specially selected plants with biological activation of the soil, taking into account the current context of soil degradation in areas affected by hostilities. An adapted algorithm for using hyperaccumulative plants is proposed, considering the types of pollution, agrophysical properties of the soil, and the possibilities of agrotechnical support.

The proposed phytoremediation technology has high practical significance as an affordable, nature-oriented, and cost-effective method of cleaning contaminated soils, particularly in the conditions of territories affected by military operations, such as the Nikopol district.

The use of phytosorption plants (sunflower, mustard, reed) ensures the effective removal of heavy metals and nitrates from the soil profile without the need for complex equipment or reagents; restoration of biological activity of soils, preservation of fertility and increase of microbial balance; reduction of risks to public health due to reduced migration of

toxicants into soil and groundwater; possibility of implementation at the level of local communities, small farms and households; cost savings compared to chemical remediation or soil removal (cost is reduced by 3-5 times); environmental safety, since the method does not involve interference with the soil structure or the use of hazardous substances. Thus, phytoremediation is a feasible and socially significant technology for rehabilitating degraded and military-affected lands, with the potential to scale up to other regions of Ukraine, especially in post-war land restoration.

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Author's contribution

Oleksandr Kovrov (professor): scientific supervision, methodology design. **Daria Kulikova** (associate professor): critical review, data curation & processing. **Mykola Kharytonov**: (professor): conceptualization, supervising the scientific and technical aspects.

All authors have read and agreed to the published version of the abstract.

The management aspect of improving energy efficiency in the residential sector based on sustainable development

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Presenting author: Alla Polyanska

Keywords: recuperation, energy, efficiency, sustainable development, water waste.

Abstract

The energy efficiency of housing is becoming increasingly important. An effective approach should be grounded in the principles of sustainable development, integrating economic feasibility, social equity, and environmental safety. Economic sustainability is achieved through the reduction of energy costs and the introduction of incentives for building modernization, which in turn fosters energy independence and the development of a stable energy market. This aligns with the United Nations Sustainable Development Goal (SDG) 7 – "Affordable and Clean Energy." Environmental sustainability is promoted through the adoption of renewable energy technologies—such as solar panels, heat pumps, and recuperators—which reduce greenhouse gas emissions and support SDG 13 – "Climate Action." Social sustainability is reflected in efforts to alleviate energy poverty and enhance living comfort, corresponding to SDGs 3 and 11 – "Good Health and Well-being" and "Sustainable Cities and Communities." A sustainable housing sector requires strategic life-cycle management of buildings, encompassing design, operation, and modernization **(Adetola et al., 2024)**. The application of green standards and circular economy principles minimizes resource consumption and extends the service life of buildings. Climate adaptation demands solutions that ensure thermal comfort with minimal energy use, alongside waste reduction and efficient resource management, in line with SDG 12 – "Responsible Consumption and Production." Thus, a management-oriented approach to energy efficiency contributes to a higher quality of life through the integration of technologies, public policy, and sustainable development strategies.

The aim of this article is to justify a management approach to enhancing the energy efficiency of buildings by applying sustainable development criteria, with a particular focus on the utilization of wastewater heat recovery systems for residential heating. To achieve this aim, the study will involve a content analysis of the concept of energy efficiency in the construction sector, an examination of the distinctions between traditional and sustainable energy efficiency management approaches, and a rationale for the sustainability of related management decisions.

The energy balance of the building gained by renewable sources is determined based on the calculation of the amount of heat obtained through wastewater heat recovery and the calculation of the amount of heat required to heat the premises. The heat demand is calculated using the formula (1):

$$Q_1 = v \cdot q \cdot \Delta T, \quad (1)$$

where are:

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Q_1 – heat demand; v – house area (500 m^2); q – specific heat load per 1 m^2 (50 W/m^2); ΔT – temperature difference (income – outcome in °C = 20 °C -12 °C = 8 °C).

To quantify the heat that can be harvested from a wastewater flow, we use Equation (2):

$$\frac{Q_2}{t} = \dot{m} \cdot c \cdot \Delta T, \quad (2)$$

where are:

$\dot{m}$ – is the mass flow rate of wastewater, kg/h; in our case 10 m³/h ≈ 10 000 kg/h;

c – is the specific heat capacity of water [~4.18 kJ/(kg · K)];

ΔT – is the temperature difference between the wastewater and the heat carrier in the heating system.

Based on the data obtained, an energy balance was constructed and the resource deficit was determined, which allows identifying additional reserves of energy supply and energy efficiency. To justify the sustainability of the solution, the sustainable efficiency of using alternative resources to obtain thermal energy from wastewater was determined by calculating the environmental, ecological, and social efficiency.

The traditional definition of energy efficiency, which is often used in technical, economic, and regulatory literature, characterizes the relationship between the useful result obtained (service, product, comfort, etc.) and the amount of energy consumed to achieve it. European documents state that energy efficiency means using less energy to achieve the same output or service (Directive 2012/27/EU). Ukrainian official sources also provide a similar definition of energy efficiency as achieving a specified level of useful energy consumption with minimal energy expenditure (The Law of Ukraine "On energy efficiency".

We propose to deepen the definition of energy efficiency in the construction sector. We define energy efficiency as the ability of a building to provide an adequate level of comfort and functionality with minimal energy consumption, achieved through the systematic implementation of managerial, technological, financial, and regulatory-strategic measures focused on sustainable development and adaptation to post-war recovery conditions. One source of energy efficiency is displaced energy – the amount of thermal energy that can be obtained from wastewater heat and which would otherwise be obtained from traditional sources (gas, coal, electricity). It is calculated in Gcal/year or kWh/year. Sewage is a specific type of municipal waste which, thanks to innovative technologies, can be a source of secondary resources, such as thermal energy. This allows it to be integrated into circular economy and sustainable development models **(Directive EU, 2018/2001)**.

In general, the concept of sustainable development has changed key aspects of energy efficiency management **(Hafez et al., 23)**. The traditional interpretation of energy efficiency focuses mainly on technical aspects – measuring energy consumption in relation to the products manufactured or the area of the facility (for example, in kilowatt-hours per m²). This approach is based on equipment modernization, thermal insulation, and other engineering solutions. At the same time, the modern paradigm of energy efficiency management proposes to consider it as a strategic tool for sustainable development **(Kosenko et al., 2025).**

An improved management understanding encompasses not only technical but also organizational, financial, and behavioral aspects **(Polyanska et al., 2024)**. We assess the technical, economic, energy, and environmental efficiency of using wastewater heat as an alternative energy source for space heating, taking into account the principles of sustainable development **(Adetola et al., 2024)**.

Calculation of wastewater mass per second:

$\dot{m}$ = 10 m^3/hour × 1000 kg/m^3 (density) = 0.00278 m^3/s × 1000 kg/m^3 = 2.78 kg/s; ΔT = 20 °C − 12 °C = 8 °C.

The heat demand is:

$$Q_1 = 500 \cdot 50 \cdot 8 = 80\,000 \text{ W} = 80 \text{ kW},$$

The thermal power extracted from the water is:

$$Q_2 = 2.78 \text{ kg/s} \times 4.18 \text{ kJ/(kg} \cdot \text{K)} \times 8 \text{ K} = 92.96 \text{ kW}$$

Thus, the thermal energy that can be obtained from wastewater is equal to 92.96 kW ~ 93 kW Taking into account the efficiency of the heat exchanger (the heat that will actually be transferred). Taking into account the efficiency of the heat pump (85 %), the thermal energy is equal to:

$$Q_{2,} = 92.96 \times 0.85 = 79.02 \text{ kW}.$$

Therefore, the adjusted thermal energy is equal to 79.02 kW. Based on the above data, we can form an energy balance for the building, which allows us to assess whether the thermal energy obtained from wastewater is sufficient to meet the heating needs of the premises:

Table 1. Energy balance

Parameter	Value
Building heat demand	80.00 kW
Available heat from wastewater	79.02 kW
Deficit/Surplus	–0.98 kW

The thermal energy obtained from wastewater almost completely covers the building's heating needs. With optimal design of the heat exchanger, underfloor heating, or other storage systems, such a system can be self-sufficient, environmentally friendly, and energy efficient. It is important to take into account actual heat losses, which also depend on heat loss through the building envelope (walls, roof, floor); air infiltration (drafts); ventilation; uneven heat supply

from wastewater (peak hours, etc.). Therefore, it is advisable to include a 10 % – 15% reserve in the heat source or combine it with an auxiliary source (e.g., a heat pump).

Table 2. Energy balance

Parameter	Value
Building heat demand	80.00 kW
Reserve for losses (15 %)	0.15 × 80 = 12.00 kW
Total demand, taking into account losses	92.00 kW
Heat from wastewater (taking into account efficiency)	79.02 kW
Heat deficit	92 – 79.02 = 12.98 kW

Thus, taking into account the reserve, the wastewater heat recovery system covers ~86 % of the building's heating needs. It is recommended to combine the wastewater system with an auxiliary heat source, such as an air-to-water heat pump or a gas boiler. Let's calculate the economic effect of using a wastewater heat recovery system compared to the cost of conventional electric heating. The calculation of the costs of full electric heating (at 16 hours of heating during a heating period of 150 days) is based on the electricity price of about 4,32 UAH per kWh.

$$Q = 92\ \text{kW} \times 16\ \text{hours/day} \times 150\ \text{days} = 220{,}800\ \text{kWh},$$
$$\text{Value} = 220{,}800 \times 4.32\ \text{UAH} = 954{,}057.60\ \text{UAH}$$

Let's calculate the costs of using heat from wastewater:

$$Q = 12.98\ \text{kW} \times 16\ \text{hours} \times 150\ \text{days} = 31{,}152\ \text{kWh},$$
$$\text{Value} = 31{,}152 \times 4.32\ \text{UAH} = 134{,}578.00\ \text{UAH}$$

The table shows the steady results of wastewater heat recovery for heating buildings.

Table 3. Effects of energy efficiency measures

Elements of permanent efficiency	Calculation	Explanation
Economic effect	954,057.60 – 134,578.00 = 819,479.60 UAH per season	The use of a heat recovery system reduces heating costs by approximately 820,000 UAH per season, which is more than 85 % savings compared to full electric heating
Environmental effect	(220,800 – 31,152) × 0.432* = 13,464.6 kg CO_2 ≈ 13.46 t CO_2	The use of a wastewater heat recovery system reduces greenhouse gas emissions by ~14 tons of CO_2 per year for a single 200 m² house.
Social impact	Reduction in household energy costs: 819 479,60/12/15 000**≈4.5 people	The social impact is an indirect result that reflects the quality of life, comfort, accessibility of resources, health care, and well-being of the population.

Notes: *Conditional CO_2 emissions per 1 kWh of electricity in Ukraine: 0.432 kg CO_2/kWh
**Average salary in Ukraine

Conclusion. Thus, based on the calculations using a comparative approach to substantiating the management principles for improving the energy efficiency of buildings, taking into account the criteria of sustainable development, it was concluded that the case study of using wastewater recovery for space heating is consistent with the principles of sustainable development and is characterized by economic, ecological, and social efficiency.

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Alla Polyanska (professor): conceptualization, investigation, and software methodology, project administration, resources, software, supervision validation, visualization. **Oleg Mykytiuk** (PhD student): formal analysis, data curation, funding acquisition, investigation. **Iaroslav Shavarskyi** (PhD): data and reference analyses.

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Improvement of the waste management process in the integrated management system of the organization

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Presenting author: Oleksandr Kovrov

Keywords: waste, process, integrated management system, risk.

Abstract

The need to improve the waste management process is due to the fundamental transformation of the waste management industry, which is moving from the traditional model of collection and disposal to the principles of a circular economy **(Abubakar et al., 2022)**. This transition is taking place under the influence of three powerful forces: regulatory pressure (EU Waste Framework Directive 2008/98/EC, which establishes a clear hierarchy of waste management; the opportunities of the circular economy, transforming waste from a liability into a valuable secondary resource, which opens up new economic horizons and generates new sources of income; the requirements of stakeholders for reliability, transparency and safety of services **(Bonifazi et al., 2025)**. Their presence creates the need to build an effective integrated management system (ISM), which will ensure the sustainability and competitiveness of organizations. A powerful ISM allows organizations to achieve synergy between quality management, environmental impact, employee health and safety, and energy consumption **(Hordiienko et al., 2017)**. The central element of the ISM, which unites all components of the system, is the risk management process, built on the basis of the standards: ISO 31000:2018 (Principles and framework), IEC 31010:2019 (Risk methods assessment) and ISO 31073:2022 (Terms and definitions) (**Cerar et al., 2022**). These standards transform the risk management process from discrete actions to a holistic, transparent and manageable process. Also, to increase the effectiveness of the IMS, the ISO 19011:2018 standard (audit guidelines) plays a key role, which is based on a risk-based approach to planning and conducting integrated audits (**Grobelak et al., 2024**). This allows to identify not only individual non-conformities, but also systemic weaknesses in the interaction between different management components. At the same time, for waste management, organizations build an environmental management system based on the requirements of the Waste Framework Directive (WFD) 2008/98/EC, which provides for a five-step waste management hierarchy **(Josimović et al., 2022)**. It is accepted as the basis for the development of national legislation in different countries of the world. The main goal of the Directive is to prevent or limit emissions into air, water and soil resulting from waste disposal, and thus reduce risks to human health and the environment. This raises the issue of building integrated management systems that combine the requirements of these standards with the development of an effective waste management process that will reduce their impact on the environment.

Analysis of recent publications shows that there is significant interest in building an effective waste management system. In the paper **(Oleniacz et al., 2025)** the authors analyzed the effectiveness of practices used by industrial

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enterprises for waste disposal and recycling. In the paper **(Ovander, 2021)**, the author proposed an algorithm for strategic environmental assessment to improve the effectiveness of strategic planning to achieve sustainable development goals, as well as waste management. In the paper **(Perkumienė et al., 2023)**, the authors proposed a synoptic risk assessment method that allows classifying landfills based on their impact on the environment and setting priorities for the necessary protective or preventive actions. In the paper **(Shahbazi et al., 2023)**, the authors recommend creating planning processes, developing policies for waste management in the context of a circular economy, improving waste processing technology, assessing the environmental impact of waste, etc. From the analysis of the presented works, it can be concluded that both systemic and detailed approaches to planning and implementing waste management strategies should be used.

The relevance of the work is associated with the search for ways to increase the organization's profitability from waste processing. To fulfill the task, there is a need to build an effective integrated management system for the organization based on the combination of four standards: ISO 9001:2015; ISO 14001:2015; ISO 45001:2018; ISO 50001:2018. An integrated management system will allow you to track the impact of waste on the environment timely and find management solutions that will allow you to find new profit opportunities. To build integrated management systems from a combination of these standards, the task that needs to be solved is to develop a risk management process that would contribute to achieving the organization's goals.

Research methods. The study is based on a comprehensive analysis of international standards ISO 9001:2015; ISO 14001:2015; ISO 45001:2018; ISO 50001:2018, operational excellence methodologies and practices of leading organizations with integrated management systems in place (**Figure 1**).

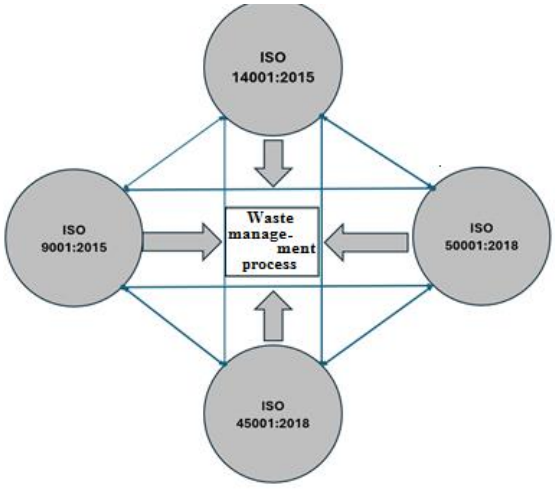

Figure 1. Key management system standards related to the waste and emissions management process.

At the same time, the solution to the problem of developing a risk management process in integrated management systems is based on a common foundation, which is a high-level structure (High-Level Structure, HLS), defined in Annex SL to the ISO/IEC directives. This structure serves as a universal architectural plan for all modern management system standards, ensuring their consistency and compatibility. For risk management in integrated management systems, a combination of HAZOP and FMEA methodologies is proposed, which allows for detailing each stage of the production process to identify hazards that generate waste.

Research results. The synergy of the standards is that they complement each other. It is proposed to consider the waste management process from the point of view of ISO 14001 requirements and their implementation is influenced by the quality of the final product (ISO 9001), safety and health of employees (ISO 45001) and energy consumption (ISO 50001). All these aspects are analyzed through the prism of risk-based thinking (ISO 31000).

For an example of the relationship between the cascading manifestation of risks of quality hazards, occupational safety and energy conservation, which lead to serious environmental consequences, we give a fragment from the definition of *Risk Priority Number* in integrated management systems of an organization from a material recovery facility (MRF): optical sorting of PET bottles. Process - optical separator, function: to identify and separate PET bottles from the flow of mixed plastics using infrared sensors and pneumatic ejectors. The results of the analysis are in **Table. 1**.

The next step is to determine the risk of cascading hazards using the HAZOP method and search for appropriate management solutions that would allow finding opportunities to increase the organization's profitability.

The ISO 14001 standard provides a framework for waste management, requiring organizations to adopt a proactive approach based on life cycle and risk-based thinking, which, in combination with the ISO 9001, ISO 45001 and ISO 50001 standards, as well as the ISO 31000 standard and its supporting tools, IEC 31010 and ISO 31073, allows building a universal methodology for identifying, analyzing, evaluating and treating any risks.

Table 1. Fragment of failure analysis during optical sorting of PET bottles

Type of failure	Potential consequences of refusal	S	Potential reasons for rejection	About	Current control measures	D	RPN	Recommended actions
Incorrect identification of PET bottle (misses PET)	1. Loss of valuable material (PET goes to waste). 2. Decrease in overall recovery rate (quality). 3. Energy loss (energy conservation) 4. Operator stress experience (occupational safety)	7	1. Dust contamination of sensor lenses. 2. Incorrect sensor calibration. 3. Wear and tear of the light source.	4	1. Weekly visual inspection. 2. Monthly calibration.	5	140	1. Implement a daily procedure to clean sensor lenses with compressed air. 2. Develop a checklist to verify calibration before each shift. 3. Install a lamp hour meter for scheduled replacement.

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Author's contribution

Vitaliy Tsopa (professor): conceptualization, data curation**, Olena Yavorska** (professor): formal analysis, **Serhii Cheberiachko** (professor): writing – original draft, **Oleksandr Kovrov** (professor): writing – review & editing, **Yuliya Pazynich** (assistant professor): reference analysis & data proceeding, **Lidia Cheberiachko** (postgraduate student): methodology verifying.

All authors have read and agreed to the published version of the abstract.

Assessment of the economic efficiency of installing geothermal systems in closed mines

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Presenting author: Dmytro Rudakov

Keywords: closed mine, mine water, heat recovery, geothermal system, net present value.

Abstract

In line with the modern trends of the power sector transition to "green energy", mine water heat recovery from closed and abandoned mines is getting active development in the world **(Walls et al., 2021)**. Geothermal potential exploration of closed mines allows for reducing emissions of harmful substances, including CO_2, SO_2, and NO_x, into the atmosphere by decreasing the consumption of fossil fuels **(Kovrov et al., 2022)**. The projects focusing on mine water heat recovery are being implemented in Germany, the UK, Spain, the Netherlands, and other countries **(Ramos et al., 2015)**. Thermal energy from mine water is extracted at geothermal systems of open type with discharge of thermally spent water to surface watercourses or water bodies (non-circulating systems) or back to the mine (circulating systems), and in geothermal probes of borehole heat exchangers with a heat transfer fluid that extracts heat without hydraulic contact with mine water (closed-loop systems) **(Banks et al., 2019)**.

Environmental benefits and prospects of recovering heat from closed mines using geothermal systems depend on multiple factors, and primarily the ratio between the cost of electricity spent on system operation for water lifting, running heat pumps, transportation of the heat transport fluid, and the thermal energy that can be extracted and delivered to consumers. So, the purpose of this study is to develop and test a robust methodology for assessing the economic efficiency of geothermal systems of various types in mines, comparing the economic settings in different countries.

As the key economic indicator of geothermal system performance, the operating income (OI) can be used. OI is calculated by subtracting operating expenses (OE), depreciation (D), and amortization (A) from gross profit (GP). In a first approximation, GP can be defined as the difference between the cost of thermal energy generated and delivered to consumers, taking into account its losses during transportation, S_{th}. The cost of electricity spent on system operation, S_{el}, can be considered as OE. D and A can be accounted through the cost of work and materials associated with the maintenance of the systems, S_{mn}. Thus, the OI can be estimated by the formulas

$$OI = S_{th} - S_{el} - S_{mn} \quad (1)$$

$$S_{th} = C_{th}\Delta t_{op} P_{th}(1 - n_l) \quad (2)$$

$$S_{el,nc} = C_{el}\frac{P_{th,nc}}{COP}\Delta t_{op}, \quad S_{el,cr} = C_{el}\left(\frac{P_{th,cr}}{COP} + P_{pw}\right)\Delta t_{op}, \quad S_{el,cl} = C_{el}\left(\frac{P_{th,cl}}{COP} + P_{pw}\right)\Delta t_{op}, \quad (3)$$

where are:

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S_{th} – thermal energy cost (€),
$S_{el,nc}$, $S_{el,cr}$, $S_{el,cl}$ – cost of electrical energy consumed during operation of non-circulating and circulating open-type systems, and closed-loop systems (€),
$P_{th,nc}$, $P_{th,cr}$, $P_{th,cl}$ – respectively, average thermal capacity of these systems (kW),
S_{mn} – costs of system maintenance (€),
C_{th}, C_{el} – tariffs for thermal and electrical energy (€/kWh),
Δt_{op} – period of system operation (h),
P_{pw} – pump power for lifting water to the surface or circulating the heat transfer fluid (kW),
COP – heat pump conversion coefficient (–),
n_l – share of thermal energy losses during its transportation (–).

Based on the reviews of current practices in mine water heat recovery and actual thermal capacities of running geothermal systems around the globe **(Banks et al., 2019; Walls et al., 2021)**, we took the following average figures for calculations: the thermal capacity of non-circulating systems $P_{th,nc}$ as 1000 kW, circulating systems $P_{th,cr}$ as 200 kW, and closed-loop systems $P_{th,cl}$ as 50 kW; COP=4; Δt_{op}=3960 h (165 days). The share of thermal energy losses, n_l, was estimated depending on the distance to the heat consumer L. The pump power P_{pw} for mine water pumping and fluid circulation was calculated following the recommendations of Larock et al. **(2000)**, with the flow rate that differs for the considered types of geothermal systems. Similarly to **(Matas-Escamilla et al., 2023)**, the maintenance costs, S_{mn}, were taken to be equal to 10% of electricity costs. The tariffs for thermal energy, C_{th}, and electric energy, C_{el}, vary over time and, generally, are set considering the annual energy consumption. Their figures for the UK, Germany, and Ukraine, according to **(Quarterly energy, 2016; Warner, 2016)**, are given in **Table 1**. The profitability indicators of geothermal systems also depend on the discount rate R that corresponds to the current interest rates on alternative capital placement (bank deposits, shares, loan bonds) in the particular country and changes over time. The values of R according to **(DHSC, 2024)** and other sources are given in **Table 1**.

Table 1. Discount rate and tariffs for electricity and heat for industrial consumers in different countries

Country	Year	R, %	C_{el}, €/kWh		C_{th}, €/kWh	C_{el}/C_{th}	
			Non-circulation systems	Circulating and closed-loop systems		Non-circulation systems	Circulating and closed-loop systems
The UK	2013	1	0.108	0.132	0.046	2.3	2.9
	2023	3.5	0.286	0.301	0.082	3.5	3.7
Germany	2013	1	0.127	0.166	0.076	1.7	2.2
	2023	2	0.207	0.249	0.12	1.7	2.1
Ukraine	2021	7	0.054		0.045	1.2	
	2023	15	0.11		0.035	3.1	

A comprehensive assessment of the economic profitability of mine-water-based geothermal systems, which includes indicators of profit, capital, and operating costs, can be performed using the generally accepted criterion of net present value NPV, which can be calculated following **Chen (2025)**. This criterion quantifies the amount of net profit that an investor can gain back from a geothermal system after the profit has covered their costs associated with installation and operation. The NPV of different geothermal systems depends on the share of additional costs, the discount rate, and the distance to the consumer of thermal energy. The results of its calculation for a period of 25 years are given in **Table 2**.

The calculations made by **Equations (1)–(3)** revealed that the ratio of the electricity tariff to the heat tariff, C_{el}/C_{th}, is the critical indicator that significantly affects the NPV of geothermal systems. For example, with a tariff ratio of $C_{el}/C_{th} \geq 3.5$, which was typical for the UK in 2023, the calculated NPV is negative. With C_{el}/C_{th} = 3.1 under Ukrainian economic conditions in 2023, the NPV could be positive only for potential non-circulating systems located at a distance of up to 2 km from the heat consumer. With $C_{el}/C_{th} \leq 2.2$, which was in Germany in 2013 and 2023, and Ukraine in 2021, the calculated NPV is positive regardless of the system type and the distance to the heat consumer. The most significant profit is expected for non-circulating systems due to significant water discharges. Increasing the distance to a heat consumer reduces the NPV of geothermal systems, which is most sensitive for closed-loop systems of low thermal capacity. The expected NPV decreases significantly when the electricity cost increases over the cost of thermal energy.

For profitable operation, the NPV must be positive. At present, the installation of geothermal systems at closed and decommissioned mines in Germany looks most attractive in terms of investment among the selected countries, considering the maritime law in Ukraine since 2022. In this case, the NPV of non-circulating systems is estimated at several million €, and circulating and closed-loop systems at hundreds and tens of thousands €. The high expected profitability indicators of geothermal systems in mines in Germany are linked with the lower values of C_{el}/C_{th} (1.7–2.2) and R (1–2%) compared to other countries.

In the pre-war period (2021), Ukraine had quite favorable tariff conditions with a low C_{el}/C_{th} ratio of 1.2, which provided positive NPV for geothermal systems of all types for the considered data ranges. The NPV could reach €1 million depending on the share of additional costs, discount rate, and distance to the heat consumer. Due to a sharp increase in electricity tariffs against the background of almost fixed tariffs for district heating services, the C_{el}/C_{th} ratio exceeded 3.0 in 2023, which caused negative NPV for geothermal systems in the country.

The C_{el}/C_{th} ratio in the UK rose to 3.5–3.7 in 2022–2023, so the *NPV* of mine-water-based geothermal systems in the UK in 2023 became negative due to a sharp increase in the cost of electricity. By 2025, due to a certain stabilization of electricity prices in the country, the C_{el}/C_{th} ratio may become acceptable again for investing in geothermal system installation at closed mines after a specific time.

Table 2. Estimated net present value *NPV* of geothermal systems, thousand €

Counrty	Year	n_{ae}, –	*L*, km	Geothermal system		
				Open type		Closed-loop
				Non-circulating	Circulating	
The UK	2013	0.2	1	943.6	–99.7	1.2
			3	470.3	–194.4	–22.4
		0.4	1	900.7	–108.3	–0.9
			3	427.3	–203.0	–24.5
Germany	2013	0.2	1	2961	187.0	79.7
			3	2179	30.6	40.6
		0.4	1	2918	178.4	77.5
			3	2136	22.0	38.4
	2023	0.2	1	4110	353.4	132.1
			3	3015	134.5	77.4
		0.4	1	4067	344.8	130.0
			3	2972	125.9	75.2
Ukraine	2021	0.2	1	1020	166.3	47.2
			3	774.5	117.3	35.0
		0.4	1	976.5	157.7	45.1
			3	731.5	108.7	32.8

n_{ae} is the ratio of additional equipment cost to the heat pump cost.

In this study, we developed a method for assessing the economic efficiency of mine-water-based geothermal systems based on the analysis of the state-of-the-art and applied technologies. It accounts for the cost of electrical and thermal energy consumed and produced during the operation, maintenance costs, and capital and technological costs associated with the installation and operation. By applying the general criteria of net present value and payback period, it becomes possible to compare promising sites for installation under varying in time economic conditions.

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Author's contribution

Dmytro Rudakov (doctor of technical sciences, full professor): conceptualization, investigation, validation, and writing – review & editing. **Oleksandr Inkin** (doctor of technical sciences, full professor): data curation, formal analysis, methodology, writing – original draft.

All authors have read and agreed to the published version of the abstract.

Hydrogen production from coal industry waste by pyrolysis: analysis of laboratory studies and prospects

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Presenting author: Eduard Kliuiev

Keywords: "hydrogen", "coal waste", "pyrolysis", "decarbonization".

Abstract

Hydrogen is recognized as a key element in formation of the future low-carbon economy and plays a crucial role in the decarbonization of the energy sector, transport and industry (**URL 1**). Its potential as a clean energy carrier and feedstock for the chemical industry is significant, as its use produces only water or water vapor, minimizing carbon emissions (**URL 2**). The International Energy Agency predicts that hydrogen could provide up to 24 % of global energy needs by 2050, contributing to a significant reduction in greenhouse gas emissions from fossil fuels (**URL 3**). Global demand for hydrogen exceeded 97 millions tons in 2023 and is expected to reach more than 100 millions tons in 2025 (**URL 4**).

Ukraine is actively integrating into global hydrogen initiatives, as confirmed by the publication by the Ministry of Energy of the draft Hydrogen Strategy until 2050. This document provides for ambitious goals for hydrogen production in Ukraine: up to 1.3 million tons in 2035 and up to 3 million tons in 2050 (**URL 5**). Hydrogen is also used in is a unique technology for large-scale long-term energy storage, which significantly improves the flexibility of the energy system and contributes to the integration of renewable energy sources (**URL 6**). Its high energy content per unit mass, where 1 kg of hydrogen is equivalent to 2.8 kg of oil or 2.1 kg of natural gas, makes it an attractive alternative to traditional fuels (**Kurt et al., 2024**). In addition, hydrogen can play an important role in sectors that are difficult to decarbonize by other means, such as freight transport, shipping and air transport, where progress is still at an early stage (**URL 2**).

The current dominance of "grey" hydrogen, which is produced mainly from fossil fuels such as methane and coal, is accompanied by significant carbon dioxide emissions (**URL 7**). This creates an urgent need to develop and implement technologies that minimize the carbon footprint, which is critical to achieving global and national decarbonization goals. The use of coal waste as a carbon-contained raw materials for hydrogen production through pyrolysis could be an important step towards obtaining "blue" hydrogen, provided that carbon capture and storage technologies are integrated. This will allow for the efficient use of available resources while reducing the environmental impact associated with carbon-contained waste.

The Ukrainian National Hydrogen Strategy and global trends highlight the growing need for hydrogen as a key element of the energy transition. At the same time, Ukraine is one of the leaders among European countries in terms of the volume of industrial waste generation, a significant part of which is coal waste (**URL 8**).

Ukraine generates about 450 million tons of such waste annually, of which over 250 million tons are coal waste, including slimes and tailings. Approximately 25 billion tons of this waste are stored in Ukrainian landfills, covering an

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area of 1,600 square kilometers, equivalent to about 4-7% of the total territory of Ukraine. According to other estimates, there are about 1,500 tailings dumps in Ukraine, covering about 165,000 hectares (**URL 9**). Projections indicate that within the next 3-5 years, a significant number of these dumps will exhaust their storage capacity, posing a threat of a large-scale environmental disaster. The main coal-mining basins of Ukraine, where this waste is concentrated, include the Donetsk (Donbas) and Lviv-Volyn coal basins.

The development and implementation of technologies for obtaining hydrogen from these waste allows not only to contribute to energy security and decarbonization, but also to solve the acute problem of disposing of huge volumes of industrial waste. This approach turns an environmental problem into an economic opportunity, creating a multifaceted positive effect for sustainable development.

Overview of basic methods.

Hydrogen production from fossil fuels is currently the dominant method worldwide, despite its significant environmental impact. The main thermochemical methods used for this purpose include steam reforming of methane, which accounts for about 95% of global hydrogen production, coal gasification, partial oxidation of hydrocarbons, autothermal reforming and hydrocarbon pyrolysis (**URL 10**). This process occurs at high temperatures (750-1000°C) in the presence of catalysts such as nickel. Coal gasification involves the conversion of coal into gas, consisting of carbon monoxide (CO), hydrogen (H_2), carbon dioxide (CO_2), methane (CH_4) and water vapor (H_2O), which can then be processed to extract hydrogen.

Pyrolysis is the thermal decomposition of carbon-contained materials in the absence of oxygen, resulting in the formation of volatile products and a solid carbonaceous residue. Fast pyrolysis is the most common variant of this method in both scientific researches and practical application. The gas formed during this process contains hydrogen, methane and carbon oxides. Scientific studies show that pyrolysis and gasification of biomass, which is an analogue of carbon-contained waste, have significant potential for sustainable hydrogen production.

Although pyrolysis is not always mentioned as a primary method for direct hydrogen production, it is an effective form of thermal destruction of carbon-contained raw materials, which generates a hydrogen. This process allows not only to obtain hydrogen, but also other valuable products, such as tar and solid residue, which increases the overall economic attractiveness of waste processing. Thus, pyrolysis can be considered as an effective intermediate step in the complex processing of coal waste.

The success of hydrogen extraction from hydrocarbons, especially from coal waste, depends largely on precise control over the technological parameters of the process. Such parameters include temperature, holding time, feedstock particle size and heating rate. The data obtained in laboratory studies allow to study in detail the relationships between these parameters and hydrogen yield, which is critical for further scaling and commercialization of the technology. This approach allows to move from a general understanding to the development of specific engineering solutions that optimize the process.

Laboratory research and results analysis.

Laboratory studies were conducted using a mixture of slime and coal in a ratio of 2 to 1, mined in the Lviv-Volyn basin. The mass of the samples was 10 g. The pyrolysis process was carried out at a final temperature of 750°C. During the experiments, the grain sizes of the starting material were varied: less than 0.1 mm, less than 0.5 mm and less than 1.5 mm. The influence of the heating rate to the final temperature of 750 °C, which was 20 minutes, 25 minutes and 40 minutes, was also investigated. The holding time at the final temperature for all experiments was fixed and was 20 minutes.

For a visual presentation and analysis of the obtained results, graphs were constructed in **Figure 1**. It displays the dynamics of gas release during the pyrolysis process for different dispersion degree and heating rates, allowing gas formation to be tracked.

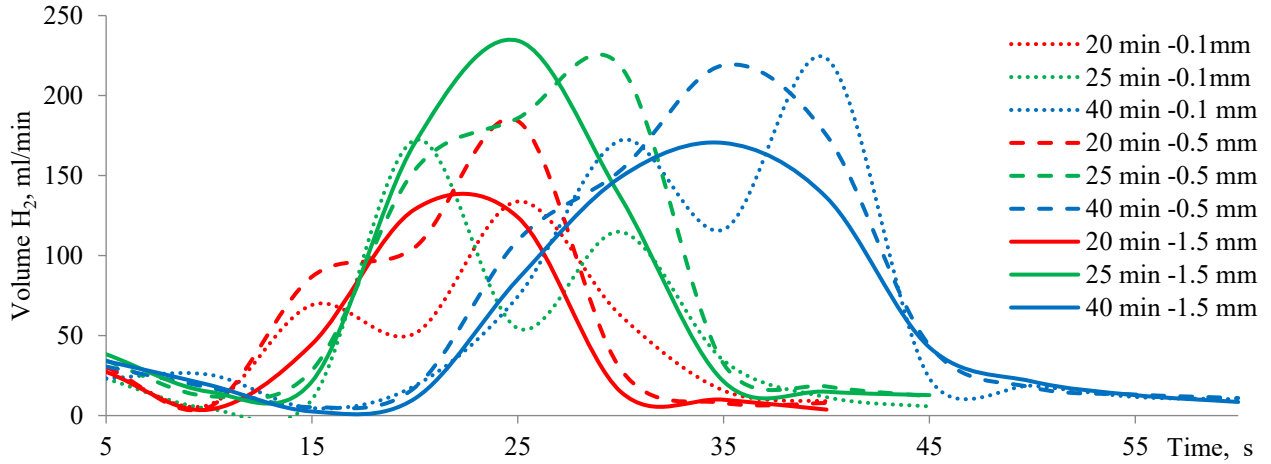

Figure 1. Dynamic of hydrogen release during pyrolysis for different dispersion degree (0.1 mm, 0.5 mm, 1.5 mm) and heating rates (20 min, 25 min, 40 min) of carbon-contained raw material

These graphs illustrate the dynamics of differential hydrogen release (gas volume in ml/min) in the pyrolysis of a mixture of sludge and coal (ratio 2:1) under different fraction size (0.1 mm; 0.5 mm; 1.5 mm) and heating duration (20, 25 or 40 min with an additional 20 min). In all experiments, uneven hydrogen release is observed: at the beginning of the process (5 min – 10 min) the gas flow is relatively small, then sharp spikes occur. Thus, for a fine fraction (0.1 mm) with a short cycle of 20+20 min there are two local maxima – about 69 ml/min at the 15th minute and about 134 ml/min at the 25th minute (immediately after heating). If the heating time is increased to 40 min, the main spike for 0.1 mm shifts to the end of heating: the highest recorded release was about 223 ml/min at the 40th minute. The peak width characterizes the optimal time during which hydrogen is released to the maximum extent.

Similarly to established dependencies, it can be seen that the intensity and time of the maximum hydrogen release depend on the heating duration: shorter modes (20+20 min) give a smaller and earlier peak, and longer ones (40+20 min) give a higher and later peak. Compared to the dispersion degree, larger particles (1.5 mm) demonstrate earlier and higher peaks at moderate heating cycles. For example, for the 1.5 mm fraction at 25+20 min, the peak of hydrogen output reaches about 234 ml/min already at the 25th minute. For the medium fraction (0.5 mm), the maximum output of about 219 ml/min was observed at about the 35th minute at 40+20 min. At the same time, smaller particles show a gradual increase in release, which reaches a maximum at the longest heating.

All curves show that after the peak, the hydrogen yield decreases sharply. Thus, larger components are prone to rapid and significant hydrogen release in the middle of the process, while small ones accumulate reaction potential and give a higher yield at long heating. This indicates that large particles, despite their greater thermal inertia, accumulate more hydrogen in the deep layers and sharply release it when reaching a critical temperature. Therefore, the balance between grain size and heating time is key to optimizing the dynamics and volumes of hydrogen release in the pyrolysis process.

Conclusions

Laboratory pyrolysis studies have confirmed the technical feasibility of effectively producing hydrogen from carbon-contained raw material formed of slime-coal in a ratio 2:1 at a final temperature of 750°C. It was found that both the grain size and the heating rate to the final temperature have a significant impact on the total hydrogen yield and the quantitative composition of gaseous products.

The results of this study demonstrate the high potential of coal waste pyrolysis as an effective and environmentally friendly method of hydrogen production in Ukraine. Further scientific and engineering researches should be aimed at comprehensive optimization of the process to achieve maximum hydrogen yield, development of effective technologies for purification and separation of gas products, as well as integration with carbon capture technologies to ensure the production of "blue" hydrogen. The implementation of such innovative technologies will contribute to achieving the strategic goals of the Hydrogen Strategy of Ukraine, improving the environmental situation in coal-mining regions through the utilization of accumulated coal-contained waste, as well as strengthening the country's energy independence.

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Author's contribution

Eduard Kliuiev (Senior Researcher): methodology, supervision, writing – review & editing. **Ruslan Ahaiev** (Senior Researcher**):** data curation, formal analysis, project administration. **Vasyl Zberovskyi** (Senior Researcher):

conceptualization, investigation, writing – original draft, **Kateryna Dudlia** (Researcher)- literature review and search, visualization.

All authors have read and agreed to the published version of the abstract.

Integration of Neural Networks into Analog-Based Methods for Assessing Technogenic Deposits for Industrial Exploitation

DIM-ESEE Conference
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Presenting author: Roman Dychkovskyi

Keywords: Artificial intelligence in mining, secondary raw materials, data-driven decision making, technogenic deposits, neural networks.

Abstract

Technogenic deposits, formed because of mining, processing, and industrial activities, represent an increasingly important category of secondary mineral resources **(Hutniczak et al., 2025; Pavlychenko et al., 2025)**. Although traditionally regarded as waste, these deposits have gained renewed attention due to the rising demand for critical raw materials and the urgent need to reduce the environmental impact of extractive industries. Analog-based assessment methods, based on comparisons with previously studied or exploited sites, have long been used as practical tools for evaluating the industrial potential of such deposits **(Polyanska et al., 2025a; Vladyko et al., 2025)**. However, the inherent complexity and heterogeneity of technogenic formations often limit the accuracy of conventional approaches.

In our previous studies, we thoroughly investigated the scale of environmental degradation caused by technogenic waste **(Miroshnykov et al., 2025)**. This is further illustrated in Figure 1, which shows the mass of contaminated land by pollutant type, measured in millions of tons. The figure provides a detailed breakdown of the total volume of affected soil for each identified hazardous substance, highlighting significant variations in contamination levels depending on the nature and concentration of pollutants present in the waste. Such visual data are crucial for evaluating the extent of environmental damage and for prioritizing remediation measures and resource recovery planning.

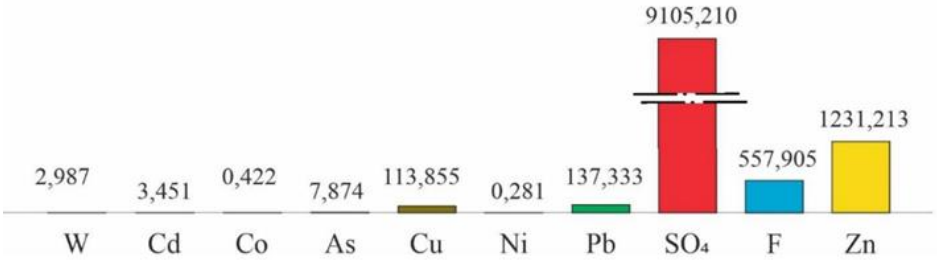

Figure 1. Mass of Contaminated Land by Various Pollutants, in Millions of Tons **(Miroshnykov et al., 2025)**.

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With global trends shifting toward sustainable resource management and the adoption of circular economy principles, the re-evaluation and utilization of technogenic deposits have become increasingly relevant. These secondary resources, often overlooked in the past, now offer strategic value due to their potential to supply critical raw materials while minimizing the need for new extraction **(Dychkovskyi et al., 2024)**. At the same time, artificial intelligence, particularly neural networks, has demonstrated remarkable capabilities in addressing complex, non-linear, and multidimensional problems across a range of engineering fields. Their ability to learn from data, identify patterns, and make accurate predictions makes them especially suitable for modeling uncertain and variable systems such as technogenic deposits **(Polyanska et al., 2023b)**. Integrating neural networks into analog-based assessment frameworks represents a promising direction for improving the precision, adaptability, and scalability of resource evaluations. This hybrid approach can compensate for gaps in historical data, reduce reliance on subjective expert judgment, and support more data-driven decision-making **(Wang et al., 2018; Bas, 2016)**. Ultimately, the application of neural networks in this context aligns with broader goals of digital transformation and sustainable resource governance in the mining and environmental sectors.

This research addresses the pressing need for intelligent, data-driven tools in resource assessment by proposing a hybrid methodology that combines the empirical robustness of analog-based methods with the predictive power of neural networks. Such integration not only improves the reliability of assessing technogenic deposits for industrial exploitation but also supports decision-making processes in resource recovery, environmental remediation, and sustainable development. The proposed approach could serve as a prototype for broader applications in mineral resource management and adaptive planning in post-industrial territories.

The research employs a hybrid methodological framework that integrates analog-based assessment techniques with artificial neural networks (ANNs) to evaluate the industrial suitability of technogenic deposits. Initially, analog-based methods are applied to identify reference cases from historical data, geological surveys, and mining records **(Bas, 2016; Gallego & Corchuelo, 2019)**. These analogs serve as a foundation for establishing baseline parameters, such as mineral composition, granulometry, contamination levels, and past recovery efficiency, which are essential for the preliminary classification of technogenic waste. Spatial, environmental, and material characteristics of selected deposits are then compiled into a structured dataset to support neural network training and validation.

The model is implemented as a multilayer perceptron (MLP) neural network, capable of processing complex, non-linear relationships between input and output data (model architecture). The network consists of an input layer, multiple hidden layers with non-linear activation functions, an output layer that generates either a prediction or a classification result **(Dyczko, 2023)**. To ensure training accuracy, a categorical loss function adapted to the specific task was employed. The general structure of the perceptron neural network can be represented as follows (**Bas, 2016; Dyczko, 2023)**

$$h(1) = \varphi(1)(W(1)xi + b(1)),$$

$$h(2) = \varphi(2)(W(2)xi + b(2)),$$

$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$

$$h(n) = \varphi\,(k)(W(k)xi + b(k)),$$

$$yi = \sigma(W(k)h(k-1) + b(k))$$

where are:
$\varphi^{(k)}$ – the non-linear activation function (e.g., ReLU),
σ – the sigmoid function,
$W^{(k)}$, $b^{(k)}$ – the weight coefficients and biases corresponding to each studied parameter.

The neural network component utilizes supervised learning algorithms, such as multilayer perceptrons (MLPs), trained on labeled data from known deposit cases. The model is optimized to predict the potential of unknown or less-documented technogenic sites based on input features derived from the analog analysis. Cross-validation techniques are employed to ensure generalizability and prevent overfitting, while sensitivity analysis is used to determine the influence of key input parameters on model output **(Kumaraswamy, 2021)**. The expert-based analog reasoning allows for both quantitative evaluation and interpretability of results **(Bas, 2016)**. This combined methodology provides a robust, adaptive, and scalable approach to assessing technogenic deposits under conditions of limited or uncertain data.

The developed multilayer perceptron model demonstrated strong predictive performance in evaluating the industrial suitability of technogenic deposits. Through training on a dataset comprising diverse reference sites characterized by various mineralogical and environmental parameters, the neural network effectively captured complex non-linear relationships that traditional analog-based methods struggled to resolve (**Bas, 2016; Dyczko, 2023; Psyuk & Polyanska, 2024)**. The model achieved high accuracy metrics, with classification accuracy exceeding 90% on validation data, confirming its robustness and generalizability across different deposit types.

Integration of the neural network predictions with analog-based assessments enabled more nuanced and data-driven evaluations of unexplored or poorly documented technogenic sites. This hybrid approach combined the strengths of empirical knowledge and machine learning, allowing for a more comprehensive analysis of complex datasets. As a result, the methodology successfully identified several previously underestimated deposits that showed promising potential for industrial exploitation. These findings were further corroborated through limited field sampling and laboratory analyses,

which confirmed the model's predictive reliability. Sensitivity analysis of the neural network model revealed that key parameters such as pollutant concentration, mineral composition, and particle size distribution exerted the greatest influence on the assessment outcomes. These insights provide valuable guidance for prioritizing future data collection efforts and optimizing monitoring strategies to improve the accuracy and efficiency of resource evaluations.

The proposed methodology proved resilient to incomplete or uncertain input data, maintaining reliable performance even when some features were missing or estimated. This adaptability underscores the model's practical applicability in real-world scenarios where comprehensive datasets are often unavailable. The results validate the effectiveness of combining neural networks with analog-based methods, offering a scalable and intelligent tool for resource managers and environmental planners focused on sustainable exploitation of technogenic deposits.

This research confirms that integrating neural networks with analog-based assessment methods enhances the evaluation of technogenic deposits by capturing complex, non-linear relationships in geological and environmental data. The proposed hybrid approach proved effective even with incomplete datasets, enabling the identification of promising secondary mineral resources and supporting more reliable decision-making. Sensitivity analysis revealed key influencing factors, guiding future data collection. Overall, the framework offers a scalable, data-driven tool that supports sustainable resource management and the responsible recovery of valuable materials from technogenic waste.

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All authors have read and agreed to the published version of the abstract.

Evaluation of sludge from the Sitarjevec mine (Slovenia) as a potential ochre pigment for concrete floor tiles

DIM-ESEE Conference
15th – 17th October 2025, Dubrovnik, Croatia

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Presenting author: Mateja Golež

Keywords: mine sludge, pigment, ochre, concrete floor tiles.

Abstract

The local community in Litija (Central Slovenia) has been intensively engaged in finding programs to revive the abandoned Sitarjevec mine for several years, so the discovery of the useful value of the mine sludge was started. Solutions are being sought to incorporate sludge into the circular loop as a potential natural pigment including for colored concrete floor tiles, which are also known from the Art Nouveau period, and today they represent floors with cultural values.

The mine sludge has been formed due to the flow of meteoric water over sulfide ores (e.g. FeS_2) just below the abandoned Sitarjevec mine (Litija, Slovenia). When these sulfides are oxidized, the oxygen in the meteoric water is gradually consumed, and soluble sulfides are mainly formed from the soluble Fe^{2+} ions. These waters travel through the rock, and when the water with Fe^{2+} comes into the mine shafts, the Fe^{2+} is oxidized to Fe^{3+} upon contact with oxygen in the air. This Fe^{3+} is not soluble in water, and so it is deposited first as an amorphous ferric oxide hydroxide-ferrihydrite, then it can show crystallization as goethite (**Toplak et al. 2021**).

The process of accumulation of mine sludge in Sitarjevec mine is continuous, because the mine shaft is partly watery and because there is an iron cover on top of the ore body. The Sava shaft, which is the outlet from the Sitarjevec mine as an acid main drainage, is the most heavily loaded. The mine sludge accumulates in the form of a thick layer and there is a risk that the tunnel will become clogged. In this case, water would be retained behind the plug, which could, with increased inflow, push the plug forward and cause a larger outflow of mine sludge into the town of Litija and the Sava River.

The Sitarjevec mine is a polymineral ore body with more than 50 different minerals, and a proportion of potentially toxic elemnts (PTEs) was also expected in the mine sludge. For the use of sludge as a pigment, mineralogical research and an assessment of environmental acceptability were therefore carried out.

The sample of mine sludge was collected from Sava shaft at the Sitarjevec mine (**Figure 1**).

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Figure 1. Location of mine sludge deposit (Sitarjevec mine, Litija, Slovenia) with sample. a) the Sava shaft acid main drainage, b) sludge sample.

The sample dried at room temperature and was characterised for its mineralogical composition by qualitative X-ray powder diffraction analysis (XRD) and chemical composition in accordance with valid standardized methods.

The results show that the mine sludge is composed of the mineral goethite (**Figure 2**).

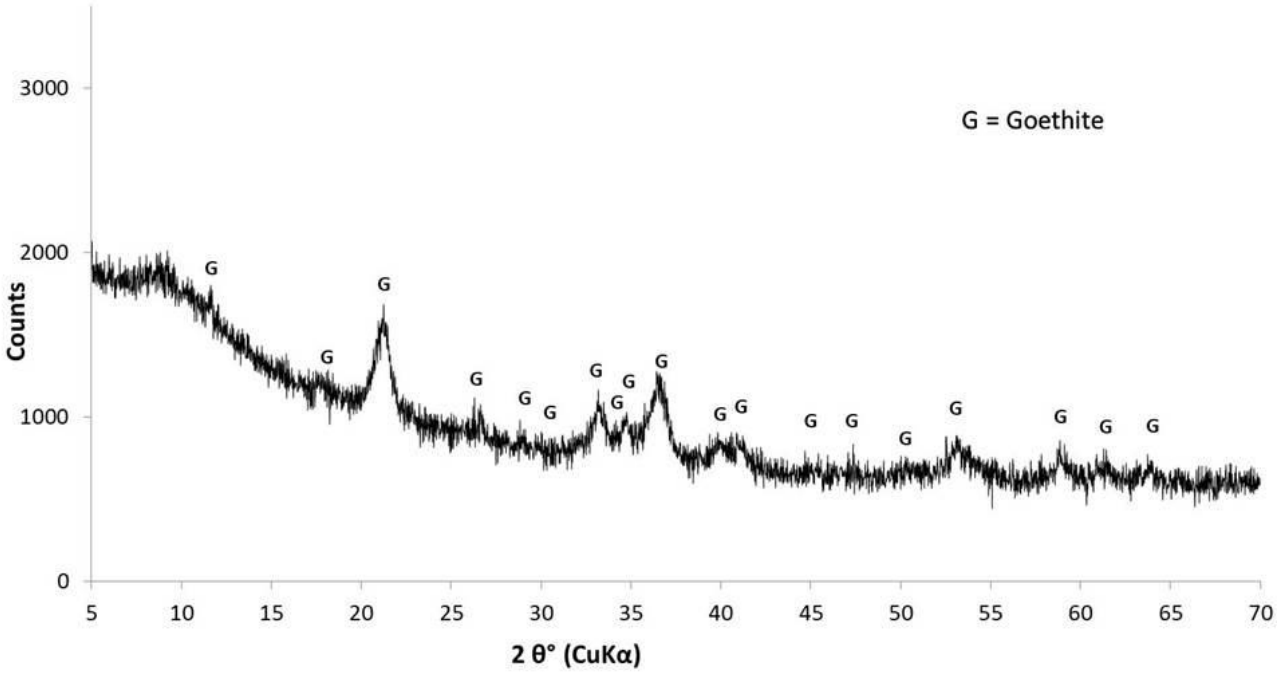

Figure 2: Mineral composition of mine sludge from the Sitarjevec mine.

A comprehensive assessment of the hazardous properties of the mine sludge sample was carried out taking into account the applicable environmental legislation, origin and composition of the mine sludge and the results of the chemical analyses of the dry sample (Eurofins d.o.o., 2025). In accordance with the guidelines of the Commission Notice on technical guidance on waste classification (2018/C 124/01), the assessment of the hazardous properties was carried out on the basis of the wet weight (as originally tested or converted from dry weight data). The results of the chemical analyses of the sample indicate that the sample does not contain organic pollutants or they are present in negligible concentrations. The sample contains elevated concentrations of manganese, iron and zinc (**Table 1**).

The measured concentrations of other metals, which could lead to the main sludge sample being assessed as hazardous, are below the minimum prescribed limit concentration of 0.1%, in accordance with Commission Regulation (EU) No. 1357/2014 and Council Regulation (EU) 2017/997. Based on generally known information and literature sources, it can be assumed that the actual subject of the investigation is limonite mud, specifically colored in orange-brown, which is given to it by its iron content. Iron and zinc as such are not classified in the list of Regulation (EC) No. 1272/2008.

Table 1. Summary of chemical analysis of dry mine sludge from Sava shaft.

	Value	Unit	Method
As	74.9	mg/kg dry matter (d.m.)	SIST EN ISO 17294-2:2017 modif.
Al	89.3	mg/kg d.m	SIST EN ISO 17294-2:2017 modif.
Sb	< 1.0	mg/kg d.m.	SIST EN ISO 17294-2:2017 modif.
Cu	< 10.0	mg/kg d.m.	SIST EN ISO 17294-2:2017 modif.
Ba	143	mg/kg d.m.	SIST EN ISO 17294-2:2017 modif.
Be	< 3.5	mg/kg d.m.	SIST EN ISO 17294-2:2017 modif.
B	< 35.0	mg/kg d.m.	SIST EN ISO 17294-2:2017 modif.
TOC	0.77	% d.m.	SIST EN 13137:2002
Zn	26086	mg/kg d.m.	SIST EN ISO 17294-2:2017 modif.
Cd	2.1	mg/kg d.m.	SIST EN ISO 17294-2:2017 modif.
Sn	< 4.0	mg/kg d.m.	SIST EN ISO 17294-2:2017 modif.
Ca	5.200	mg/kg d.m.	SIST EN ISO 17294-2:2017 modif.
Mg	< 3.00	mg/kg d.m.	SIST EN ISO 17294-2:2017 modif.
Na	< 3500	mg/kg d.m.	SIST EN ISO 17294-2:2017 modif.
Co	213	mg/kg d.m.	SIST EN ISO 17294-2:2017 modif.
Cr	< 5.0	mg/kg d.m.	SIST EN ISO 17294-2:2017 modif.
Mn	71660	mg/kg d.m.	SIST EN ISO 17294-2:2017 modif.
Mo	< 2.0	mg/kg d.m.	SIST EN ISO 17294-2:2017 modif.
Ni	216	mg/kg d.m.	SIST EN ISO 17294-2:2017 modif.
Se	< 35.0	mg/kg d.m.	SIST EN ISO 17294-2:2017 modif.
Pb	82.2	mg/kg d.m.	SIST EN ISO 17294-2:2017 modif.
Si	28600	mg/kg d.m.	SIST EN ISO 17294-2:2017 modif.
Ta	< 3.5	mg/kg d.m.	SIST EN ISO 17294-2:2017 modif.
V	< 3.5	mg/kg d.m.	SIST EN ISO 17294-2:2017 modif.
Ti	< 40.0	mg/kg d.m.	SIST EN ISO 17294-2:2017 modif.
Fe	458658	mg/kg d.m.	SIST EN ISO 17294-2:2017 modif.
Hg	0.13	mg/kg d.m.	ISO 167722:2004 brez točke 7.4.2 modif.
S	0.11	mg/kg d.m.	ASTM D 4239(C):1997

Based on the aforementioned research, it is estimated that the sample taken from the Sava shaft, currently treated as waste, does not exhibit hazardous properties. Based on previous research that has yielded positive results regarding the potential use of mine sludge (ochre natural pigment) for construction products, further investigations are underway regarding its potential use for concrete floor tiles. The concrete floor tiles will be used for the renovation of cultural heritage buildings.

The useful value of the ochre sitarjevec pigment has also been proven in painting, where it shows stable color Ocher pigment is also used for colored preparatory layers , because it prevents the colors from fading into the ground in oil painting technique.

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Author's contribution

Mateja Golež (PhD): conceptualization, investigation, methodology, writing, review & editing. **Marija Đurić** (PhD): investigation, validation, writing, review & editing. **Katarina Šter** (Bsc. Geol.): conceptualization, investigation, methodology, writing, review & editing. **Sabina Dolenec** (assistant professor): conceptualization, investigation, methodology, writing, review & editing.

All authors have read and agreed to the published version of the abstract.

Investigation of Coal Reserve Recovery Indicators in Low-Capacity Mines Considering the Reprocessing of Mining Waste

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Presenting author: Oleksandr Mamaikin

Keywords: productive flow, cluster, operational scenario, elasticity.

Abstract

The mining industry in Ukraine is undergoing transformational changes. Currently, there is a need not only to develop innovative approaches to optimize the parameters of rare earth metal deposit development but also to create conditions for the efficient extraction of industrial reserves. Coal mining in Ukraine exhibits specific characteristics that distinguish this sector from others. One of the primary challenges is the lack of effective reforms and development (or transformation) strategies for the industry. In the early 2000s, an attempt was made to modernize coal mining enterprises, resulting in a production increase of 15 % - 20 % **(Bazaluk et al., 2022; Bondarenko et al., 2025).** The article **(Makarov et al. 2022)** provides an analysis of the technical and economic performance of mines from 2004 to 2018, indicating that 57 % of enterprises could not achieve the minimum required loading level at the longwall. Active military operations in eastern Ukraine since 2014, followed by a full-scale military invasion, have accelerated trends of uncontrolled production capacity reduction. This has led to contradictory approaches ("recipes") proposed for the further development of the industry between 2014 and 2025 **(Malashkevych et al., 2022; Petlovanyi et al., 2018; Boichenko, 2019)**. Additionally, there is an issue with the conceptual design approach. A coal mine is considered an enterprise focused on extracting a mineral resource–coal **(Jeong et al., 2016; Calzada Olvera et al., 2023).** If it is a mine, extraction occurs underground; if it is an open-pit, extraction is conducted open-cast methods. From an economic perspective, a mine is a single-profile enterprise. However, in reality, the end consumers of its products are the energy and metallurgical industries, and others **(Matebese et al., 2024; Zhou et al., 2024)**. Even today, in 2025, vertically integrated companies exist that encompass a full cycle of mineral extraction and energy generation **(Narkhede et al., 2023).** Therefore, designing a mining operation for a specific type of mineral without assessing the feasibility of extracting associated minerals is economically unjustified **(Rosa et al., 2024)**. We propose considering a mine as an enterprise whose efficiency is derived from primary and secondary productive flows **(Lousada et al., 2024)**. For a coal mine, the primary flow is coal, while secondary flows include waste rock, methane gas, and water. Depending on the stage of the enterprise's lifecycle, the configuration of these productive flows varity. Finding a balance between these flows enables the achievement of maximum profitability.

The objective of this study is to investigate the production indicators of low-capacity underground coal mines under various configurations of productive streams during the final extraction of industrial reserves, with consideration of the feasibility of coal mining waste reprocessing. This work presents a novel approach by analyzing performance parameters of low-capacity coal mines (up to 300,000 tonnes per year) operating with mechanized technologies at depth, within the

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context of coal region transformation. The study covers mines in Ukraine and selected Eastern European countries (Czech Republic and Poland), where similar transitions of the coal sector are taking place. The analysis is based on empirical data from 2008 to 2022, including operations in Donetsk, Luhansk, Dnipropetrovsk, and Lviv regions. The dataset includes mining-geological and technological indicators, as well as information on raw material quality measured by ash content. The research also aims to assess the potential for waste reprocessing and extraction of associated mineral resources by justifying parameters for the depletion of industrial reserves, which are determined by the ratio of coal extraction (as the main productive flow), coal enrichment and waste reprocessing (as auxiliary streams), and the quality characteristics of extracted coal.

To simulate the performance indicators of low-capacity coal mining enterprises, the Cobb–Douglas production function was applied. We proposed a model for the efficient operation of coal mining enterprises under conditions of industrial reserve depletion. The model is based on the principle of finding a balance between the productive flows that can be generated by the enterprise. Each productive flow may exhibit a certain elasticity. Elasticity defines the percentage change in output in response to a one-percent change in any of the input factors, assuming the others remain constant. Finding a balance between these flows allows for the identification of an operational state with the highest profitability. The objective function of the proposed model is to determine the output volume of the primary mineral resource, the amount of mining waste to be reprocessed, and the minimum ash content of the extracted mineral. Based on the estimation of elasticity coefficients, we conducted simulations of the configurations of productive flows—coal, methane gas, rock mass, and water—under various coal quality indicators. To describe the strategic behavior of the mines, clustering was performed using dendrogram-based analysis. During the research, the configurations of productive flows, ash content of coal, and coal production volumes were varied.

We've developed specialized software for analyzing industrial reserve development scenarios. **Figure 1** illustrates a graph showing the search for the optimal configuration of production flows based on ash and coal production. For each scenario, the program generates 3D surfaces and creates profit heatmaps depending on coal ash and coal production.

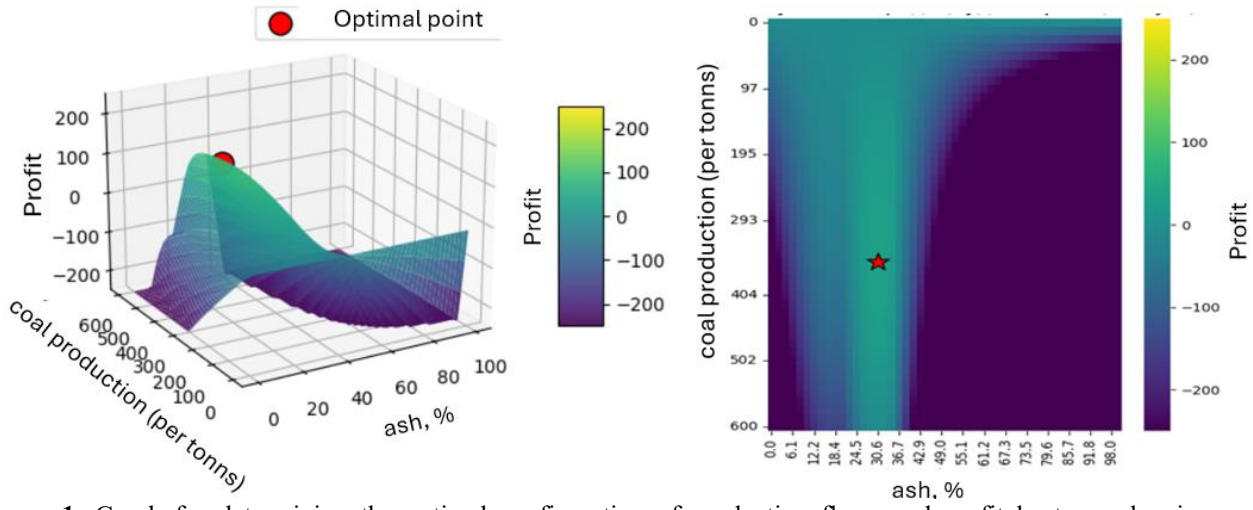

Figure 1. Graph for determining the optimal configuration of production flows and profit heatmap showing dependence on coal production and ash

In the course of the research, a novel approach was developed for modeling the production performance of coal mining enterprises operating under conditions of industrial reserve depletion, with consideration of coal mining waste reprocessing. Four production scenarios were simulated, each representing a distinct operational context—ranging from conventional coal extraction with the absence of certain productive flows to scenarios lacking coal production entirely. It was established that as coal quality improves, its share in the overall production balance increases regardless of the operational scenario. When the ash content of coal is below 20 %, it is advisable to prioritize increased coal extraction, while the relevance of mining waste reprocessing declines, and wastewater treatment becomes economically unjustifiable. The study confirmed that under conditions of low ash content, coal remains the primary productive flow irrespective of extraction volumes. Furthermore, methane recovery from underground spaces in low-capacity coal mines appears economically unviable across all assessed ash content; levels. As a result, the configurations of productive flows were defined for various industrial scenarios.

The scientific novelty of the study lies in the development of a new approach for justifying the parameters of reserve depletion in low-capacity coal mining enterprises within the context of coal region transformation. Based on modeling, four types of low-capacity coal mines were identified according to the configuration of productive flows. For the first time, cluster boundaries were defined and accompanied by a corresponding technological description. Classifying an enterprise into a specific cluster enables the formulation of an appropriate operational strategy and the application of optimization and production management methods aimed at enhancing efficiency and rationalizing the parameters of coal deposit exploitation.

The practical significance of the study lies in the verification of an approach based on the application of the Cobb-Douglas function to identify optimal configurations of productive flows. Using the Analytic Hierarchy Process (AHP), the hypothesis regarding the elasticity of productive flows was confirmed **(Ait-Mlouk et al, 2019; Liao et al, 2023)**. A decision support system in the form of dedicated software was developed to model performance indicators of low-capacity coal mines.

The presented study expands the frontier of research on the operational dynamics of coal mining enterprises in the context of post-mining and sustainable resource extraction management. The obtained results can be applied in the development of transformation strategies for coal-intensive regions.

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Author's contribution

Andrii Khorolskyi (associate professor): scientific supervision, methodology design. **Oleksandr Mamaikin** (associate professor): critical review, funding acquisition, English language support. **Victor Lapko** (post graduate student): data curation & preprocessing. **Ivan Sheka**: (associate professor): model development and testing, formal analysis, validating results. **Svitlana Delehan**: (associate professor): conceptualization, supervising the scientific and technical aspects.

All authors have read and agreed to the published version of the abstract.

Enhancing thermoelectric response in cement composites by introducing industrial by-products

DIM-ESEE Conference
15th – 17th October 2025, Dubrovnik, Croatia

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Presenting author: Mateja Štefančič

Keywords: cement composites, industrial waste (by-products), thermoelectricity, energy harvesting, mechanical properties.

Abstract

The rapid evolution of construction technologies and the growing demand for sustainable, energy-efficient and material-efficient infrastructure have spurred interest in smart and multifunctional materials. Among them, the cement-based composites with thermoelectric (TE) capabilities have emerged as promising candidates. These materials are capable of converting temperature gradients into electrical energy via the Seebeck effect, enabling applications such as energy harvesting, self-powered sensors, and real-time infrastructure monitoring **(Snyder et al., 2008).** This research, conducted within the HEU LIAISON project, investigates the potential of incorporating secondary raw materials (i.e. recycled waste) and industrial by-products into cementitious composites to enhance their thermoelectric performance. The broader aim of the project includes the design of thermoelectric generators (TEGs) for integration into railway infrastructure. However, this presentation focuses specifically on the material-level development of cement-based composites with improved TE functionality.

Integrating thermoelectric properties into cementitious materials addresses multiple critical goals. Firstly, it supports the circular economy by reclaiming industrial waste or by-products that might otherwise contribute to environmental degradation, especially in the form of natural resource depletion and increased global warming potential due to the forecasted longer transport routes to dedicated landfills for industrial waste and primary raw materials production. Secondly, it creates opportunities for energy-autonomous infrastructure systems by converting otherwise wasted heat into useful electrical energy. These multiple benefits situate thermoelectric cement composites at the intersection of sustainable construction and functional material innovation.

Historically, thermoelectric materials have been confined to semiconductors such as bismuth telluride (Bi_2Te_3) or lead telluride (PbTe), which exhibit high electrical conductivity (σ), large Seebeck coefficients (S), and low thermal conductivity (κ)—the three parameters that define the thermoelectric figure of merit (zT), given in **Equation 1**:

$$zT = \frac{\sigma S^2 T}{\kappa} \quad (1)$$

In contrast, cement-based materials are typically poor electrical conductors that exhibit low Seebeck coefficients, which initially excluded them from consideration in possible thermoelectric applications. This perception changed in the late 1990s, when studies revealed that incorporating conductive fillers, such as carbon fibres, into cement matrices could

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yield detectable thermoelectric effects. For example, **Chung (1998)** demonstrated that carbon fibre-reinforced cement composites could achieve Seebeck coefficients around 17 μV/K, marking a turning point in the field. The formation of cement composites with improved thermoelectric properties is schematically shown in **Figure 1**.

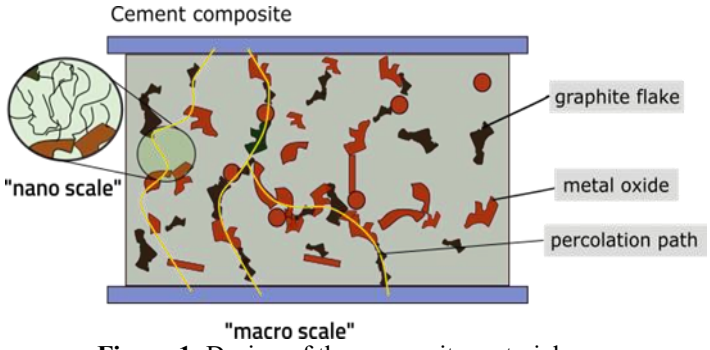

Figure 1: Design of the composite material.

In this study, we build on this earlier work by exploring the impact of several industrial waste and by-products on the thermoelectric behaviour of cement composites. The selected secondary raw materials (SRMs) include:

- red mud (a by-product of bauxite refining),
- copper slag, air (dry)-granulated and water (wet)-granulated,
- sandblasting powder from steel manufacturing,
- sludge from a Pb-Zn mine and
- graphite, in both commercial and recycled forms (e.g., from spent pot lining - SPL).

These materials were chosen based on their elemental and mineralogical compositions, especially the presence of conductive phases and semiconductive metal oxides such as ZnO and Fe_2O_3. These oxides, when finely dispersed in a cement matrix, contribute to the enhancements of the Seebeck effect and support intrinsically low carrier mobility in the cement-based composites **(Kumar et al., 2021)**. Similarly, carbon-based additives such as graphite, carbon black, and carbon fibres form conductive pathways (percolation paths) that significantly improve the composite's electrical conductivity, a critical precondition for efficient thermoelectric behaviour. **Pan et al. (2020)** demonstrated that cement composites incorporating recycled carbon fibres exhibit significantly improved electrical conductivity and power output without severely compromising mechanical performance when filler content is optimised.

For each SRM, a series of composite mixtures was prepared by replacing 1 wt % – 20 wt % of Portland cement. After a standard curing period, the samples underwent extensive testing. Mechanical properties were assessed through 28-day compressive and flexural strength tests to ensure structural integrity. Thermoelectric performance was evaluated by measuring the Seebeck coefficient (S), electrical conductivity (σ), and, where possible, thermal conductivity (κ). Additionally, all mixtures were characterised for elemental and mineralogical composition using X-ray fluorescence (XRF) and powder X-ray diffraction (XRD) techniques, respectively. Environmental safety, including leaching behaviour, was also assessed for each material.

The experimental methodology emphasised comparative analysis. Each material's performance was benchmarked against reference cement mixes to evaluate the degree of thermoelectric enhancement and its compatibility with mechanical performance requirements. Several correlations emerged between the chemical and mineralogical compositions of the additives and their resulting thermoelectric properties. For instance, samples containing red mud displayed at 50 °C a Seebeck coefficient of 2×10^5 μV/K, representing an eightfold increase compared to the reference cement mixtures (2.5×10^4 μV/K), suggesting effective thermoelectric conversion potential. Importantly, these enhancements did not come at the cost of unacceptable losses in mechanical strength, provided the filler content remained within optimal limits.

A key outcome of this study is that experimental cementitious composites incorporating SRMs exhibit several features typical of efficient thermoelectric materials, including enhanced electrical conductivity at elevated levels, high Seebeck coefficients, and intrinsically low thermal conductivity. Although the individual zT values remain lower than those of high-performance semiconductors, the composites' structural durability and potential environmental benefits indicate their suitability for future integration into large-scale infrastructure. Moreover, environmental safety assessment showed that the leaching behaviour of all tested experimental composites remained within permissible limits.

This investigation also serves as a critical step towards the design of full thermoelectric generators (TEGs) based on cementitious matrices. Although the generator-level results are beyond the scope of this presentation, it is important to note that the insights gained from material characterisation will inform the selection and optimisation of materials for such devices. The ability to tailor thermoelectric behaviour via industrial by-product selection provides a valuable design lever for future TEG development.

Furthermore, this work aligns with broader European objectives related to resource efficiency, circular economy, climate-neutral infrastructure, and innovation in construction materials. The reuse of industrial waste or by-products not only reduces landfill burden but also introduces added-value applications for materials traditionally seen as environmental

liabilities. For example, red mud, often difficult to dispose of due to its chemical composition, demonstrated promising thermoelectric and mechanical properties when incorporated into cement composites.

In conclusion, this study demonstrates that cement-based materials enhanced with carefully selected industrial by-products can achieve measurable thermoelectric functionality. The ability to convert ambient heat into electrical energy, combined with acceptable mechanical performance and the environmental advantages of waste valorisation, positions these composites as promising candidates for the next generation of smart, energy-harvesting infrastructure. Continued research will focus on further optimising material formulations, enhancing *zT* values, and scaling up production toward real-world applications, particularly in the context of railway systems and other civil engineering structures.
While challenges remain—particularly in achieving high conversion efficiencies and long-term durability—the progress to date indicates that thermoelectric cement composites could play a vital role in low-carbon construction systems. By combining material science, environmental sustainability, circular economy and infrastructure innovation, this approach lays the groundwork for smart and circular engineering solutions in the built environment.

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Author's contribution

Mateja Štefančič (PhD): conceptualisation, methodology, investigation, formal analysis, writing – original draft. **Mateja Košir (PhD):** conceptualisation, formal analysis, validation, writing – review & editing. **Slavko Bernik** (PhD): conceptualisation, data curation, writing – review & editing. **Alenka Mauko Pranjič** (PhD): funding acquisition, supervision.

All authors have read and agreed to the published version of the abstract.

Hydration and Carbonation Behaviour of Selected Recycled Materials from Slovenia

DIM-ESEE Conference
15th – 17th October 2025, Dubrovnik, Croatia

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Presenting author: Vesna Zalar Serjun

Keywords: hydration, carbonation, recycled materials, combustion ashes.

Abstract

Industrial by-products are gaining attention as sustainable alternatives to primary raw materials. In the construction sector, which consumes vast amounts of resources, their use aligns with the goals of the European Green Deal. Two key characteristics supporting their use are hydraulic reactivity and CO_2 capture potential—where the former enables binding capacity and the latter contributes to reducing the carbon footprint by sequestering CO_2 and offsetting the need for conventional binders.

This study investigates industrial by-products from combustion processes, focusing on their hydration behaviour and capacity for mineral carbonation. Various types of combustion ashes were hydrated under different water-to-binder ratios, with curing monitored over time. Carbonation was studied under semi-dry conditions and varying CO_2 concentrations, with emphasis on how phase composition evolved with moisture, CO_2 levels, and curing duration.

Most tested materials displayed hydraulic activity, though the degree varied. The lowest hydration reactivity was observed in ashes not collected via electrostatic precipitation. In contrast, paper ashes showed the highest reactivity due to their rich calcareous phase content. The amorphous phase content in coal and co-combustion ashes strongly influenced hydration mechanisms.

Carbonation tests on co-combustion ash showed that lime transformed into calcite and other hydrated products, with higher moisture content and longer curing times (24 hours) enhancing slightly the carbonation process.

Hydration and carbonation processes occurred simultaneously and interacted in complex ways. Hydration products such as $Ca(OH)_2$ and ettringite were prone to carbonation, while the formation of $CaCO_3$ as a carbonation product could influence both the kinetics and nature of further hydration. These interactions suggest that a detailed understanding of the combined hydration–carbonation process is essential for optimizing the performance of such alternative binders.

Future work will focus on identifying the most influential parameters governing these processes, aiming to enhance the practical application of industrial by-products in sustainable construction materials.

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Author's contribution

All authors have contributed to: conceptualization, investigation, draft and manuscript preparation.
All authors have read and agreed to the published version of the manuscript.

Electrochemical-assisted metal recovery from end-of-life products using a two-stage process

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15th – 17th October 2025, Dubrovnik, Croatia

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Presenting author: Guillermo Pozo

Keywords: electrochemical, end-of-life-metal recovery.

Abstract

TECNALIA is developing a two-stage process to recover metals from end-of-life products using the electrification of a leaching process. In the first stage (LX), we combined the spent solid residue with a selective DES chemistry to enrich the Ag, Cu and Sn content from the initial sample. In the second stage (ELX1), we electrify the leaching process to improve the extraction yield of the target elements and selectively recover by electrodeposition on the cathode electrode. This approach will considerably reduce the use of chemicals, improving the economy compared to the SoA technologies and reducing GHG emissions. The ELX stage considers a combination of DES and mild aqueous solutions of NaCl (e.g., 0.5 M), to dissolve metals from solid materials selectively. The polarization of the electrodes will promote the production of oxidizing agents at the anode, such as hydroxyl radicals and hydrogen peroxide (hence avoiding their external addition), releasing the metals from the solid residue. The simultaneous electrodeposition of metals achieved the selective recovery of target elements, depending on the physicochemical features of the solid input residues and the operational conditions employed. For example, after treating a PV scrap sample, the element composition analysis of the cathode showed a metal product of 92 % Cu, 5 % Fe and 2% Ag. Using another end-of-life product with Sn content (17 %), we achieved a metal product of 88 % Sn and 9 % Fe.

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[1] EP4490346A1 - An electrochemical process for recovering platinum group metals (pgms) from solid residues - Google Patents.

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EIT labelled Innovative Mineral Resource Exploration Joint Master Programme run by five universities – TIMREX

DIM-ESEE Conference
15th – 17th October 2025, Dubrovnik, Croatia

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Presenting author: Ana Maričić

Keywords: TIMREX, EIT Label, Mineral Exploration, double-degree programme

Abstract

TIMREX (T-Shaped Master Programme for Innovative Mineral Resource Exploration) is a double-degree, EIT-labelled, master programme run by five universities – University of Miskolc (UM) from Hungary, Wroclaw University of Science and Technology (WUST) from Poland, Luleå University of Technology (LTU) from Sweden, University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering (UNIZG-RGNF) from Croatia and Technical University of Leoben (MUL) from Austria. Nationally accredited Master Programmes of the university partners contribute to the TIMREX programme. Programmes are Earth Science Engineering MSc, TIMREX specialisation at UM, Mining and Geology MSc, Mineral Resources Exploration specialization at WUST, MSc programme in Exploration Geoscience, TIMREX specialisation at LTU, Applied Geology and Geological Engineering MSc, Exploration and Environmental Geology module at UNIZG-RGNF and International Master of Science in Applied and Exploration Geophysics (IMAGE), branch TIMREX at MUL. As student mobility is an essential and integrated part of the TIMREX joint master programme a total of ten tracks is offered between these five universities. During the programme, every student will study in at least two university partners. The students in the first year have opportunity to enrol in three universities UM, UNIZG-RGNF and WUST. While on the second-year students have a two-semester mobility to four partner universities – UM, WUST, LTU and MUL. After that, students receive two diplomas from two partner universities – first- and second-year university.

Besides two diplomas the programme offers many other opportunities to enrolled students. As the program is designed in partnership with industry partners and leaders in the mining, geological and environmental spheres students will gain direct insight into real-world challenges and market needs. In addition, students will experience cross-sectoral activities such as practical teaching, internship, fieldwork and summer field camp, as emphasis in TIMREX focusses on field research, laboratory exercises and industry projects. Accordingly, the programme provides experience that is directly applicable to the job market. Specific elements of the programme such as international mobilities, mentoring programme conducted by geoscience professionals from the industry, field work and internships open the door to an international career.

Emphasis is on an interdisciplinary approach combining knowledge from geology, mining, geophysics, earth sciences, engineering, the environment, sustainability and digital technologies. The TIMREX programme received the EIT Label

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qualification in 2022. This label requires the incorporation of specific competence developing elements such as innovation, entrepreneurship, leadership, sensitivity towards sustainability and intercultural issues. Therefore, students will also develop soft skills as focus is on teamwork, communication, project management and problem solving. During the study students work with the latest tools and software used in the industry (GIS, 3D modelling, simulations, etc.). These are all key skills that employers are increasingly looking for.

The programme is supported by the EIT-RawMaterials through an education project which continues the project that established the joint master programme. The second project – TIMREX-CRM – develops the joint curriculum in two important directions: extension towards the prospecting and exploration of critical and strategic mineral resources and in this way to contribute to the implementation of the EU CRM Act, and incorporation of deep-tech solutions during the courses and additional program elements.

Specific objectives of the programme are:

1. To strengthen mineral exploration in Europe, by supporting the intensification of mineral exploration across Europe, particularly in under-explored regions such as the Carpathian-Balkan, Iberian, Fore-Sudetic, Irish-British, and Ukrainian Shield areas, in line with the CRM Act's goal of increasing domestic production of critical raw materials up to 10 %.
2. To develop professional workforce with exploration technologies and skills for Europe, by integrating the use of deep-tech applications, geoscientific data integration, 3D modelling, and digitalization of archive exploration data to improve the efficiency and sustainability of mineral exploration. Ensure that students and professionals acquire skills aligned with the evolving technological and regulatory landscape, including the application of UNFC classification and EU Taxonomy for sustainable mining practices.
3. To strengthen international collaboration between partner universities and the attractiveness of their study programmes to young non-EU talents, by addressing the shortage of well-trained mineral exploration professionals and attracting young talents through specialized education programs. Additionally, the programme will foster international cooperation by engaging non-EU students from resource-rich countries, enhancing EU's resource diplomacy, and contributing to responsible sourcing strategies for securing critical raw materials.

The main aim of the TIMREX master study programme is to enhance Europe's mineral exploration capacity by fostering technological innovation, workforce development, and international collaboration to ensure a secure, sustainable, and diversified supply of critical raw materials in alignment with the CRM Act and EU strategic goals.

Acknowledgment

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Author's contribution

Sibila Borojević Šoštarić: conceptualization, writing—original draft preparation and editing. **Ana Maričić**: conceptualization, writing—original draft preparation and editing. **Ferenc Madai:** conceptualization, writing and editing. **Nils Jansson:** writing—review and editing. **Gabriela Paszkowska:** writing—review and editing. **Frank Melcher:** writing—review and editing.

Integrative Field Learning in the Raw Materials Sector: The ADRIA fieldtrip Component of the EMerald MSc in Georesources Engineering

DIM-ESEE Conference
15th – 17th October 2025, Dubrovnik, Croatia

Sibila Borojević Šoštarić[1] ✉, **Tomislav Brenko**[1] ✉
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Please mark in what field is your Abstract (mark with "x" your selection):

Field	
Raw materials prospection and discoveries	
Mining methods	
Geometallurgy and sustainable extraction	
Materials recycling and waste management	
Raw materials education	x

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YES	NO
	x

Mark your preferred presentation mode:

Oral	Poster	No preference
x		

Presenting author: Tomislav Brenko

Keywords: EMerald, Adria fieldtrip, EIT Label, Erasmus Mundus

Abstract

The EMerald Master's Programme is a two-year, 120 ECTS joint degree in Resources Engineering, collaboratively organised by four European universities: the University of Liège (ULiège) in Belgium, the University of Lorraine (UL) in France, the Luleå University of Technology (LTU) in Sweden, and the Technische Universität Bergakademie Freiberg (TUBAF) in Germany. This multidisciplinary program focuses on key aspects of Resources Engineering, specifically resource characterisation, processing, modelling, and management. Its structure spans four semesters, each accounting for 30 ECTS, with students spending the first semester in Liège, the second in Nancy, the third at either LTU or TUBAF, and the fourth at one of the four partner universities, depending on the student's academic and research preferences. The programme is designed to provide a balanced education that integrates geological knowledge of metal and mineral resources, such as reserve characterisation, landfill and urban mining, and modelling, with process engineering skills, including comminution, sorting, extractive metallurgy, and sustainable waste disposal. This interdisciplinary framework is delivered through a combination of lectures, industry-focused seminars, and collaborations with business schools, giving students a comprehensive introduction to the raw materials sector and preparing them for real-world industry challenges.

A key component of the programme is the ADRIA field trip, implemented as part of the EMeraldinho projects, which seeks to enhance students' exposure to the European raw materials sector. The ADRIA field trip is designed to immerse students in the practical aspects of the raw materials value chain. Its primary goal is to deepen understanding of the full exploration and exploitation process, from initial geological surveys to the final stages of resource extraction. By engaging with real-world sites and professionals, students gain valuable insight into the geological processes that form ore deposits, the diversity of deposit types, and the methods used to extract these resources in efficient and sustainable ways.

To prepare students for this intensive field experience, a series of ADRIA KTI case-specific lectures are delivered in advance, providing foundational geological knowledge about the Adria region, aimed especially at students without a strong background in geology. The content covers a wide range of relevant topics, including ore types, genetic deposit models, mineral reserves and production, industrial development, manufacturing processes, waste management, site operations, safety measures, and energy efficiency. Each of the six lectures is structured around a specific phase of the Wilson Cycle and a corresponding deposit type, covering significant examples such as the Late Permian Ljubija iron deposit, Early Triassic polymetallic Veovača deposit, Cretaceous Borov Dol copper-gold deposit, Jajce bauxite deposits, Oligocene Sasa lead-zinc mine, and the Miocene lithium-boron deposits in the Pannonian Basin. These 90-minute sessions

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help students grasp the geological evolution of the Dinarides and prepared them to actively contribute to fieldwork and case discussions during the trip.

The ADRIA field trip usually lasts 11 days and takes students across four countries: Croatia, Bosnia and Herzegovina, Serbia, and North Macedonia. During the trip, students have an opportunity to explore six different types of mineral deposits, each selected for its relevance to specific stages of the raw materials value chain. The daily activities are carefully aligned with the mining and processing characteristics of each site. To optimise the learning experience, students are divided into smaller groups. Each group receives a detailed field guidebook containing descriptions of the local and regional geology, as well as mining and processing methods. Additionally, field workbooks are provided to facilitate practical tasks tailored to each site. These tasks encourage critical thinking and hands-on engagement by prompting students to investigate geological formations, mineralisation processes, and operational methods directly in the field.

By the end of the ADRIA field trip, students are able to:

(1) Integrate geological, mineralogical, and alteration data across diverse raw material deposits by:
    a. Identifying and classifying rock types, mineral compositions, and alteration styles for various mineralization systems, and
    b. Interpreting field relationships between host lithologies, mineralisation, and fluid pathways.
(2) Explain field geochemical and analytical techniques by:
    a. Interpreting portable XRF data in the context of lithology, alteration, and mineral assemblages,
    b. Observing macro and microelement variations across provided datasets,
    c. Creating and interpreting correlation matrices to explore geochemical trends and alteration indicators including:
        i. Magnesite: Explain what Mg/Si ratios reveal about carbonation intensity and alteration zones (proximal/distal); analyse Cr, Ni, V presence and their linkage to ultramafic protoliths,
        ii. Bauxite: Discuss carbonate composition, bauxite mineralogy, Fe/Ti potential reuse, trace element impacts in red mud waste,
        iii. Polymetallic VMS deposit: Locate hydrothermal mineralisation zones, assess evidence of hydrothermal overprint in deep marine sediments, and identify geochemical signatures (e.g., Ba, Mn, REE, As) linked to sedimentary vs. hydrothermal processes.
(3) Evaluate industrial raw material processing and sustainability issues by
    a. Describing the industial process and material flow from input to waste generation (examples: gossan type iron-ore processing, VMS ore processing, Bayern process (bauxite))
    b. Quantifying energy consumption and analysing energy source mix (electricity, steam, fossil fuels),
    c. Assessing waste composition, management, reuse potential, and environmental risks,
(4) Demonstrate critical thinking and applied problem-solving through:
    a. Proposing sustainable or circular process improvements across the raw materials value chain,
    b. Justifying environmental or technological interventions at industrial and deposit levels,

Parallely to the field activities, students are working in groups and developing ADRIA deposits related case-studies contributing to their ability to:

(1) Critically evaluate the raw materials value chain of a selected deposits (e.g. iron, alumina, copper, lead-zinc, lithium, graphite), identifying key challenges such as low investment, outdated technology, poor waste management, and environmental or social constraints.
(2) Synthesize and interpret technical and policy-related backgound information from literature, presentations, and field insights to identify gaps or misfits across exploration, mining, processing, waste handling, and end-use stages.
(3) Identify cross-sectoral synergies taking into acount existing infrastructure, data, or projects to enhance the sustainability or economic viability of the selected case-study.
(4) Design and deliver a professional 10-minute pitch, presenting a concrete and innovative solution to an identified challenge, supported by backgound data and multi stakeholder analysis.

Presenting evidence-based conclusions by linking field observations, geochemical data, and broader resource management frameworks (e.g., the EU CRM Act) and case-study presentations, the ADRIA field trip is widely regarded as a valuable and successful educational experience. It significantly enhanced students' understanding of the raw materials industry, improved their field-based competencies, and reinforced their academic learning. By interacting directly with experts from academia and industry, students developed the confidence and skills needed to navigate the complex landscape of the European raw materials sector. EMerald Master's Programme, through its integrated academic curriculum and the immersive ADRIA field trip, offers a robust and forward-thinking education in Resources Engineering. The combination of theoretical instruction, industry engagement, and field-based learning prepares students to address the current and future challenges of sustainable raw materials management in Europe. The ADRIA component, in particular, serves as a model for learning, enhancing both technical knowledge and practical skills essential for successful professional development in the raw materials sector.

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Author's contribution

Sibila Borojević Šoštarić: conceptualization, writing—original draft preparation and editing. **Tomislav Brenko**: conceptualization, writing—original draft preparation and editing.

Developing practical competencies in Social License to Operate - The PRO-SLO PhD School case study: Vareš, Bosnia and Herzegovina

DIM-ESEE Conference
15th – 17th October 2025, Dubrovnik, Croatia

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Materials recycling and waste management	
Raw Materials Education	x

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	x

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Oral	Poster	No preference
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Presenting author: Marta Mileusnić

Keywords: Social License to Operate (SLO), stakeholder engagement, interdisciplinary learning, PhD training, participatory resource management

Abstract

In the raw materials sector, traditional STEM education often lacks a strong focus on generic and soft skills, particularly those required for meaningful engagement with non-professional stakeholders. Addressing this gap is essential for fostering responsible and sustainable resource management, especially in relation to public acceptance and the Social License to Operate (SLO). The PRO-SLO Pilot PhD School was developed in response to this need. It is an innovative international program that offers an interdisciplinary and practice-oriented learning experience for doctoral candidates across Europe. The school is structured into three modules combining theoretical instruction, collaborative research, and fieldwork. Upon completion of all components, participants receive 4 ECTS credits.

This presentation outlines the development and implementation of the second and third modules of the PRO-SLO Pilot PhD School, an innovative educational program focused on the concept of Social License to Operate (SLO) within the mineral resources sector. Following an introductory first module centered on theoretical foundations, the second and third modules aim to deepen understanding and apply acquired knowledge within the specific context of Bosnia and Herzegovina, with a special focus on the mining region of Vareš. The emphasis lies on gaining practical insights into the significance of SLO for sustainable resource management projects and engaging directly with local stakeholders to address real-world challenges and develop effective communication strategies.

The second modules was conducted as a twelve-week online collaboration, during which students, organized in interdisciplinary teams, worked on a detailed analysis of complex aspects related to SLO in the context of Vareš and the broader Bosnian region. The teams were carefully composed to maintain gender balance and to include at least one South Slavic language speaker, facilitating access to original literature in local languages. Each team focused on one of five key themes: geographical and historical context, mining industry image and legacy, major socio-economic challenges, socio-environmental conflicts, and the legislative framework for mining and environmental permits. The methodology included literature review, online research, social media analysis, and regular mentoring sessions to monitor progress and resolve challenges. At the conclusion of this module, students prepared and presented their research findings, which laid the groundwork for the practical work in the subsequent third phase. Through this process, they developed key competencies such as the ability to analyze interconnections between social, legal, and historical factors in resource governance, evaluate socio-economic and environmental impacts of mining, and synthesize information from diverse sources.

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Furthermore, working in multicultural teams enabled them to strengthen collaborative skills and apply contextual insights to broader discussions on Social License to Operate.

The third module took place as an intensive five-day onsite program in Vareš, providing students with the opportunity to apply their theoretical and research knowledge through direct engagement with diverse local stakeholder groups. Students were divided into four groups, each focusing on a specific stakeholder category: vulnerable members of the community (including war victims and elderly individuals), stakeholders whose livelihoods depended on natural resources, residents living in close proximity to mining sites, and project-dependent secondary beneficiaries such as local authorities and educational institutions. This phase involved thorough preparation, focus group meetings with stakeholders, data analysis, and the development of tailored communication strategies addressing concerns about environmental impacts and compensation, while also highlighting potential benefits such as job creation and community development. Through these activities, students enhanced their ability to identify and analyze key stakeholders, prepare and conduct focused and inclusive discussions, and interpret stakeholder feedback critically. They also gained experience in formulating context-sensitive communication strategies and presenting their recommendations clearly and persuasively. Working in interdisciplinary teams further strengthened their capacity to collaborate effectively and respond adaptively to complex, real-world challenges.

In addition to working sessions, the program incorporated cultural activities that enabled students to deepen their understanding of the local context. At the end of the onsite week, students presented their findings and strategies to industry and academic mentors and subsequently compared their proposals with the real-world approaches currently employed by Adriatic Metals in stakeholder engagement. This reflection further enhanced their comprehension of the challenges involved in balancing diverse interests and the importance of transparent, adaptive communication to obtain and maintain a Social License to Operate.

Through these two modules, the PRO-SLO Pilot School demonstrates a unique and comprehensive approach to educating doctoral candidates in sustainable resource management by linking theoretical knowledge with practical application and interdisciplinary teamwork. This approach equips students with the competencies necessary for effective understanding and implementation of the SLO concept, which is essential for the future of responsible mining practices.

Acknowledgment

Sincere gratitude is extended to Adriatic Metals for their exceptional contribution to the success of the PRO-SLO Pilot PhD School. Their active involvement in the conceptualisation, planning, and implementation of the onsite component in Vareš was crucial in shaping a meaningful and practice-oriented learning experience. The company generously provided access to their facilities, delivered insightful presentations on the social and economic dimensions of their operations, and enabled students to directly engage with key stakeholders. Their openness, logistical support, and warm hospitality greatly enriched the fieldwork phase, offering a unique opportunity for students to explore the challenges and opportunities of achieving Social License to Operate (SLO) within a real-world mining context.

Acknowledgements are also extended to all contributors involved in the PRO-SLO Pilot PhD School for their support and collaboration. The project is led by Montanuniversität Leoben, Austria, with contributions from the following consortium partners: AGH University of Science and Technology; Luleå University of Technology; Mineral and Energy Economy Research Institute of the Polish Academy of Sciences; National Technical University of Athens; Technical University in Graz; TU Bergakademie Freiberg; Polytechnic University of Madrid; and the University of Zagreb Faculty of Mining, Geology and Petroleum Engineering.

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Author's contribution

Marta Mileusnić (Full Professor): conceptualization, investigation, methodology, project administration, resources, writing original draft. **Sibila Borojević Šoštarić** (Full Professor): conceptualization, investigation, methodology, and writing review and editing. **Vildana Mahmutović**: conceptualization, investigation, methodology and writing review and editing. **Arnela Babić**: conceptualization, investigation, methodology and writing review and editing, **Ben Huxtable:** conceptualization

All authors have read and agreed to the published version of the abstract.

Training needs of copper sector employees in the context of digital and environmental transformation: results of the SkiComCu project

DIM-ESEE Conference
15th – 17th October 2025, Dubrovnik, Croatia

Jolanta Religa[1], Ireneusz Woźniak[2], Malwina Kobylańska[3], Katerina Adam[4], Malgorzata Kowalska[5]
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YES	NO
x	

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Oral	Poster	No preference
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Presenting author: Malwina Kobylańska

Keywords: lifelong learning, competences, competence gaps, competency profiles, copper industry

Abstract

The research work presented in the article concerns the identification of competency gaps of the employees of the copper sector, a sector strategic for the development of the EU economy, especially in the context of the green transition. Within challenges facing the copper sector, the human resource and skills shortages become more and more urgent. The present research, conducted within the SkiComCu-LL project funded by EIT RM aimed at identifying the competency gaps of selected groups of the current and future employees of the copper industry in Europe. The methodological approach included a triangulation of methods: desk research, on-line survey (directly in the work environment, for key competence profiles selected by project partnership as strategic for the future of the sector) and participatory assessment - interviews with representatives of different groups of copper sector employees (Focus Groups Interviews). Competence' gaps were analysed in two categories: technical and social competencies. It was shown that copper processing is a highly specialized field, requiring to integrate basic knowledge and skills in STEM, e.g. physics, chemistry, mechanics with modern automation and digitalization, including virtual and augmented reality (VR, AR) applications. The results obtained are the basis for formulating a proposal for training topics and developing training materials corresponding to the real expectations of both current and future employees of the copper sector companies.

Materials and methods

The primary objective of the undertaken activities presented in this article was to identify and analyse the training needs of selected occupational groups employed in the copper (Cu) sector, with particular emphasis on countries covered by the EIT Regional Innovation Scheme (RIS), where the need to foster innovation capacity is greater.

The research methods used: desk research, on-line survey, focus group interviews (FGI). The research covered employees working in the following enterprises: KGHM Polska Miedź S.A., ELVALHALCOR Hellenic Copper and Aluminium Industry S.A., Aurubis Bulgaria AD.

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The document analysis encompassed an extensive review of the relevant literature (including academic publications and industry reports), as well as institutional documents related to human resources systems, provided by the industrial partners of the SkiComCu project.

The methodological approach adopted in this study aimed to identify competency gaps among employees in the copper (Cu) sector, with reference to a set of strategic competency profiles defined by the SkiComCu partnership as essential for the sector's sustainable development.

Stage 1 – Development of Key Competency Profiles for the Copper Sector

Based on document analysis, a review of relevant source materials, and the methodological expertise of the project team, six competency profiles were identified as strategic for the further development of the copper sector, as defined by the SkiComCu partnership:

1. Miner – Operator of Self-Propelled Mining Machines (EQF Level 3)
2. Mineral Processing Technician (copper ore) (EQF Levels 4 and 5)
3. Mining Engineer (Senior Mining Supervisor) (EQF Levels 6 and 7)
4. Mining Geologist (EQF Levels 6 and 7)
5. Metallurgical Engineer – Non-Ferrous Metals (EQF Levels 6 and 7)
6. Copper Recycling Process Engineer (EQF Levels 6 and 7)

Stage 2 – Identification of Skill Gaps (Online Survey – CAWI)

The second stage involved an online survey (Computer-Assisted Web Interviewing – CAWI), designed specifically for each of the six strategic competency profiles. A diagnosis of both professional skills and social competences was undertaken.

As already noted the survey targeted copper sector employees working in mining and processing companies operating in countries covered by the RIS scheme. Respondents included employees at various organisational levels whose job roles aligned with the identified profiles, as well as their direct supervisors. A total of 250 complete responses were collected. The questionnaires were made available via a hyperlink or QR code.

Stage 3 – Identification of Skill Gaps (Focus Group Interviews - FGIs)

The third stage consisted of focus group interviews (FGIs), aimed at deepening the insights obtained through the online survey and identifying current and future skill gaps in the copper sector workforce.

FGIs were conducted using a semi-structured interview format. An interview scenario and guidelines for the interviewers were developed.

The focus group interviews were organized and conducted (May-June 2024) with the involvement of key industrial partners of the SkiComCu project, with the participation of employees of the copper companies representing three RIS countries: Poland, Greece and Bulgaria. The target groups in each country (8-12 selected people) included: middle management and technical staff, senior management, administrative and office staff, HR staff.

Participants met face to face in each of the three countries and discussed the situation of human resources in the copper sector, focusing on several neutral and unambiguous exploration questions.

Discussions were run by moderator/ facilitator (as an active participant), according to the scenario. The moderators were experienced researchers representing the SkiComCu project partnership institutions, familiar with the full context of the research being conducted. After the interviews, the moderators prepared summaries with the results of the discussions, which were further analysed by a team responsible for the research component of the project.

Results

The studies on competence gaps among employees in the copper sector in selected European countries conducted within the SkiComCu project were innovative. They focused on a specific group of employees of a larger sector (non-ferrous metals sector), i.e. employees of copper ore mining, processing and manufacturing.

The survey covered 5 employee groups profiles that the project partnership identified as key for the future of the sector. The selection and description of key competence profiles for selected employee positions was preceded by in-depth desk research as well as expert knowledge of the industrial partners of the SkiComCu project – key industrial companies in the copper industry in Europe.

However, the respondents to the surveys and FGIs also indicated a number of very specific skills, closely related to the key competence profiles for the copper sector, e.g.: comprehensive understanding of metallurgy principles and processes; storage, loading and transport processes for solid copper mineral processing products.

Based on the survey results it was deduced that in the copper ore mining and processing sector, the working positions related to the recycling of copper-containing materials is not considered as a separate profession. Professional tasks related to this important area of operation of copper industry enterprises are performed by representatives of professions such as e.g. metallurgical engineers. The increasing importance of recycling processes in the overall management of copper

resources, justifies the assumption that this will probably prove to be insufficient in the near future where engineers specialising in the recovery of copper from production waste will be needed.

In the context of constant and dynamic change, it is important that companies in the Cu sector consider their workforce as a valuable asset to grow, rather than a fluctuating resource, expendable in response to volatile changes in external environments. Aling these lines, the mining labour force needs to be equipped not only with the skills necessary now, but also skills of the future, i.e. future- proof skills. Location of new copper resources and reserves requires geological and dta processing expertise Mining operations require skilled workers who can incorporate innovative and more sustainable methods, operate heavy equipment, exhibit IT skills and ensure the safety of workers and the environmental protection as well as the establishment of active communication with the relevant stake holders. Processing copper ore into usable metal requires ore characterization, chemical, and metallurgical expertise. Obtaining the necessary environmental permits and other approvals requires regulatory and technical expertise across a number of disciplines and competencies to achieve and retain social acceptance.

Copper sector companies, especially from RIS EU territories, should continuously invest in training programs to develop the skills and expertise needed to meet the demand for the sustainable copper production. This could include apprenticeships, internships, Life Long Learning programs, or specialized programs to move across sectors. Therefore, the results obtained and presented at the present study provide the basis for formulating a proposal for training topics and developing training materials corresponding to the real expectations of current and future employees as well as copper sector companies.

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Author’s contribution

Jolanta Religa (PhD): conceptualization, formal analysis, investigation, methodology, project administration, supervision and writing – original draft. **Ireneusz Woźniak** (PhD): data curation, investigation, methodology, visualization and writing – original draft. **Malwina Kobylańska** (PhD Eng.): formal analysis, funding acquisition, project administration, resources and writing – original draft. **Katerina Adam** (Professor): formal analysis, investigation, funding acquisition, resources, supervision and writing – review & editing. **Małgorzata Kowalska** (PhD): data curation, investigation, resources, validation and writing – review & editing.

All authors have read and agreed to the published version of the abstract.

EPICENTRE LCA summer school

DIM-ESEE Conference
15th – 17th October 2025, Dubrovnik, Croatia

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Presenting author: Davor Kvočka

Keywords: Life Cycle Assessment (LCA), circular economy, summer school, sustainability, business development

Abstract

Life Cycle Assessment (LCA) is a widely used method for environmental assessment of products, processes and services. LCA enables decision-makers to identify the most significant areas of impact and implement strategies for improvement. However, LCA analysis is a complex process with a high potential for mistakes, while final readers often lack the necessary expertise to fully understand the objective and results of an LCA study. Misunderstanding and misinterpretation of LCA results can thus lead to sub-optimal decision making or erroneous conclusions. Therefore, there is a need to equip early-career researchers and practitioners with advanced knowledge and practical skills in LCA methodology, its application and effective communication of LCA results.

This paper presents the organisation and implementation of LCA summer school developed within the EPICENTRE project, which aims to bridge the gap in comprehension and communication surrounding LCA. EPICENTRE's summer school is based on a comprehensive and dynamic educational platform that integrates e-learning, simulations and workshops, thus ensuring an innovative and engaging learning experience for participants from industry and academia. The summer school development process included identifying key knowledge gap and learning objectives aligned with ISO 14040/44 standards, selecting relevant case studies, designing on-line and hands-on sessions using open source LCA software tools, implementing advanced approaches combining economic and social analyses, and integrating practical information on the sue of professional LCA software and preparation of environmental declarations.

Experts from academia and industry were invited to deliver lectures and interact with participants, providing both depth and diversity in content delivery. Participants presented findings in a final symposium, which fosters peer-to-peer learning and networking. Finally, feedback was collected to assess the clarity and effectiveness of the course structure, content and delivery, thus providing valuable information for future improvements of the learning materials and course structure. The first iteration of summer school demonstrated that a well-structured course can significantly enhance competencies in life cycle thinking, analytical modelling and environmental assessment of both researcher and industry experts with limited prior knowledge in LCA.

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MINERS educational project in mine safety and mine rescue

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Presenting author: Dalibor Kuhinek

Keywords: safety in mines, mine rescue school.

Abstract

The MINERS (Mine Emergency and Response School) project was a joint project involving Montanuniversität Leoben (MUL), TU Bergakademie Freiberg (TUBAF), University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering (UNIZG-RGNF), Trinity College Dublin, DI Wilhelm Schon and Boliden Mineral AB. The project was led by Hannes Kern from MUL. The project duration was from 1.1.2018. to 1.3.2020. It was funded as EIT RAW Materials project.

The aim was to bring together students from different universities as well as experts from industry, to work together during field exercises and small research and innovation projects. MINERS project partners created a common curriculum for the education module as well as training and education material. The module consists of different theoretical and practical training topics, supported by a newly developed handbook for mine rescue and emergency response at the university level.

The cooperation of different universities formed a unique international training program for educating future leaders and experts. MINERS as well builds a basis for young entrepreneurial and innovative engineers in the field of mine safety and emergency response (Kern et al., 2017).

Figure 1. Miners emblems created for future advertising

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The goals of this project were:

- Compare practices and procedures in mine safety and mine rescue in Croatia, Germany and Austria
- Create a curriculum on the topic of mine rescue for students
- Make a manual for mine rescue teaching
- Make trial mine rescue education for up to 30 students from few different universities

The education module was split into two parts. The first part is a training and exchange program that combined theoretical lessons as well as hands on exercises during three workshops. Each workshop lasted one week. The students were attending all three workshops, and the majority of teaching staff were present on all workshops (**Figure 2, 3** and **4**).

Students learned the basics and standards for mine emergency response and rescue operations. Joint field exercises attended by all participating universities and supported by experts from the mining industry helped the students to develop their knowledge. The focus was on specific topics like mining accidents and mine rescue operations. To connect the participating students and to have access to the best infrastructure available, the courses was held at different locations (Zagreb, Freiberg and Leoben).

Part two was an individual learning and work phase. Participating students were working on individual topics in cooperation with industrial partners between the workshop in Freiberg and the workshop in Leoben (Kern et al., 2017; Kern et al., 2020).

The plan was that 30 students would participate in the project and 28 students attended and successfully finished MINERS program (10 from Leoben, 4 from TUBAF and 14 from UNIZG-RGNF). All students were awarded a scholarship for travel and accommodation expenses. During the selection process, criteria like gender balance as well as professional competences did play a major role.

Figure 2. Workshop in Zagreb (5th – 9th March 2019)

Figure 3. Workshop in Freiberg (24th – 28th June 2019)

All goals of the project were met.

In addition, the project enabled students and lecturers from related fields to enjoy valuable social interactions and to exchange experiences with colleagues from other countries.

Figure 4. Workshop in Leoben (21th – 25th October 2019)

The project was successfully finished, exceeding goals, thanks to the effort and hard work of all those involved, primarily the project leader, Hannes Kern. Also very important contribution was made by Professor Helmut Mischo from TUBAF. Also, many thanks to Mr. DI Wilhelm Schön who contributed to the success of the project with his experience.

Sadly the outburst of corona-virus stopped all plans for further cooperation.

When the Faculty of Mining, Geology and Petroleum Engineering, University of Zagreb started working on upgrading the MSc study program in Mining (2022.), the elective course MINERS was added as a new course.

Figure 5. Picture from real-life execise during a Workshop.

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Author's contribution

Dalibor Kuhinek (professor**): c**onceptualization, writing—original draft preparation and editing, **Mario Klanfar** (associate professor): writing and editing, **Vinko Škrlec** (associate professor): writing and editing, **Vjekoslav Herceg** (senior assistant): writing and editing.

All authors have read and agreed to the published version of the abstract.