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Quantification of the Economic Efficiency of Innovative Technologies in the Mining Industry using Monte Carlo Simulations

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Abstract

The study analyses the economic efficiency of innovative technologies in the mining industry. Using an extensive modelling of Monte Carlo simulations, including 150 random scenarios, we quantify the impact of the implementation of autonomous drilling systems (AI), drone fleet using LiDAR technology and software, and IoT-based predictive maintenance using a digital twin on key performance indicators, such as the return on investment (ROI), internal rate of return (IRR), and net present value. The results show a direct correlation between reduced downtime and improved economic indicators, with a significant impact on energy consumption and CO_2 emissions. A representative scenario confirmed the synergistic effects of innovations on economic efficiency and environmental sustainability. The study highlights the importance of innovative technologies for modernising the mining industry and provides a tool for strategic investment decisions.

Keywords
mining industry, innovation, economic efficiency, Monte Carlo simulation, predictive maintenance, sustainability.

Introduction and Literature Review

In the global economy, where the mining industry faces increasing demands for efficiency, sustainability, and social responsibility, the application of innovative technology has proven critical to achieving competitiveness. This paper aims to analyse the impact of technological and process innovations on the performance and sustainability of mining companies. The mining industry, a strategic pillar of the global economy, plays a key role in supplying raw materials to sectors such as construction, energy, and technology. However, traditional mining methods have become unsustainable due to various factors, including rising costs, resource depletion, tightening environmental regulations, and shifting societal expectations. As such, it has become inevitable to implement innovative technologies and procedures to enable more efficient and responsible mining of non-renewable resources.

Balci and Kumral (2022) emphasise that innovation is crucial to securing the growth and sustainability of the mining industry and highlight the need for an innovation strategy grounded in the sector's structural characteristics. The plan should enable mining companies to respond efficiently to growing demand for renewable energy sources and ensure their competitiveness in the dynamic market. At the same time, Kashan et al. (2021) identified key organisational cultural values essential to supporting innovation and highlighted the importance of an open, flexible culture for the successful integration of new technologies and innovative approaches. Similarly, Yudhistyra and Srinuan (2024) highlight the importance of employees' attitudes towards innovation as a key factor in the adoption of new technologies, especially generative artificial intelligence (GenAI), underscoring the need for organisational culture and attitudes. Vargas and Lorenzo (2024) analyse the impact of leadership on organisational climate for innovation, finding a strong link between transformational leaders and support for innovation, suggesting that leaders' ability to motivate employees plays a key role in the success of innovative projects.

Modern analyses of mining technology show that innovative approaches, such as artificial intelligence and automation, play a key role in enhancing the security and efficiency of mining companies' operations. On the other hand, a study by Zhang et al. (2014) evaluates the efficiency of technological innovations in the traditional mining sector, with results suggesting low innovation efficiency and highlighting the urgent need for additional investments in technology and research. Klein et al. (2015) focus on the crushing process and its impact on energy efficiency, noting that innovation in this area has advanced slowly and recommending the implementation of local guidelines for technological readiness as a tool to accelerate innovation cycles. Liang et al. (2024) analyse the impact of artificial intelligence on the sustainability of the mining industry in China and find a significant positive correlation between innovation and sustainable development.

The study by Varava and Kovalchuk (2010) underscores the importance of innovation management tools for the successful implementation of new technologies. Ranose et al. (2020) analysed the innovation activities of mining companies and identified the need to implement process innovations in response to growing demands for competitiveness and environmental protection. Lay et al. (2022) developed a process innovation model that highlights the importance of involving various stakeholders at different phases of the innovation process. Townson et al. (2013) demonstrate how design-led innovations can help resolve conflicts between a company and the market and suggest several strategies to expand innovation and improve agility in a turbulent market. Yudhya (2018) evaluates the impact of governing partnerships and business innovation on the performance of a limestone mining company in Indonesia, highlighting the importance of strategic alliances.

Fan et al. (2017) found that innovation elements, including government support and employees' technical qualifications, positively impact economic growth in the Chinese mining industry. Sánchez and Hartlieb (2020) underscore the critical role of digital transformation and tool innovations in improving efficiency and lowering costs. Nicolas et al. (2020) studied the impact of economic activity on "soft" innovations in the mining industry in Chile. They found out that oil prices have a direct effect on investments and expectations. Jovanovic et al. (2023) examine the relationship between knowledge management and green innovations and confirm that the implementation of sensible technologies leads to sustainable development that integrates economic, environmental, and social factors. Zuo et al. (2022) apply a two-stage DEA model to evaluate technological innovation and ecological efficiency in the Chinese mining industry. Adomako and Nguyen (2023) studied the impact of social legitimacy on environmental innovations and observed that efficient green management enhances the positive impact of this legitimacy on innovation activities. Jianchun (2024) assesses the effects of ecological mining practices on corporate sustainability in China and finds that these practices have a significant positive impact on innovation and organisational commitments to sustainable development.

Bartos (2007) identifies the mining industry as a sector that achieves an innovation pace comparable to traditional industries but with lower productivity than high-tech sectors. Olvera (2022) emphasises that declining ore quality poses further challenges for innovation. Menghetti (2005) warns that adaptation has become a key factor in survival for isolated mining sectors in Australia's unfair mining industry. Reshetilova and Nikolayeva (2011) address problems with implementing innovations in the Ukrainian mining sector. Daly et al. (2021) discuss global challenges to the innovation process in the mining industry. Faltholm and Norberg (2017) study the relationship between gender diversity and innovations in the mining industry. Stubrin (2017) examines opportunities for innovation and diversification in Chile's mining industry, focusing primarily on suppliers with high knowledge intensity (KIMS). Ananeh-Frempong (2022) examines innovation among suppliers in Ghana's gold mining sector. Prokopenko et al. (2022) focus on dialectic contradictions in the innovation intelligence of mining engineers.

Mugebe et al. (2023) propose a framework for evaluating the impact of innovations in mining technology on companies' market value. Alessandri (2025) investigates the relationship between patents and profitability, noting their positive correlation with innovation, while warning about the need for proper supplier restrictions. Pous de la Flor et al. (2023, 2024) discuss new uses of coal mines as potential energy generators and storage locations and apply the AHP algorithm in the identification of suitable abandoned underground mines of the energy accumulation infrastructure.

Innovation is crucial for the sustainability and competitiveness of the mining industry. A successful implementation of technology requires a favourable culture and efficient management. Although technological innovations such as AI and automation hold great potential, they need targeted investments to become genuinely effective. Process innovations and stakeholder involvement play a critical role. Economic and environmental contributions range from economic growth to sustainable processes. Overcoming specific challenges and looking for new opportunities, such as using abandoned mines, is inevitable. Innovation activities require a holistic approach that considers strategic, technological, organisational, economic, environmental, and social factors to achieve more efficient, sustainable mining.

Research Methodology

The economic impacts of implementing innovative technologies at a mining company were modelled using a Monte Carlo simulation. For this approach, we generated 150 random scenarios representing various levels of machine downtime reduction, ranging from 27% to 83%. This range was determined through consultations with experts and analyses of technical feasibility, accounting for the specific characteristics and potential impact of each implemented innovation: autonomous drilling systems (AI), a fleet of drones equipped with LiDAR technology and software, and IoT-based predictive maintenance using a digital twin.

A detailed computational model was subsequently applied to each generated scenario to assess the link between downtime reduction and relevant economic parameters. As a next step, the downtime-reduction percentage generated for each scenario was applied to each machine type in mining operations. This application led to a direct reduction in each machine's fuel consumption and, at the same time, to an increase in the total volume of non-renewable resources extracted. The decrease in fuel and electricity consumption also led to lower greenhouse gas emissions, indicating that the implemented innovations may have a positive environmental impact. All quantified variables were then included in the complex discounted cash flow (DCF) model, which simulated the project's financial performance over 10 years. The variable discount rate of 3–6% used in the simulations reflected the estimated capital costs and the level of investment risk in the field.

By applying the DCF model to each of the 150 scenarios, we obtained the distribution of values for key economic efficiency indicators of the project, including the net present value (NPV),

$$NPV = \sum_{t=0}^{n} \frac{CF_1}{(1+r)^t} \tag{1}$$

internal rate of return (IRR),

$$0 = \sum_{t=0}^{n} \frac{CF_1}{(1+IRR)^t} \tag{2}$$

return on investment (ROI)

$$ROI = \frac{Profit\ - Cost}{Cost} \times 100 \tag{3}$$

Afterwards, a statistical analysis of these distributions was performed to determine the mean indicator values. The scenario in which the IRR, NPV, and ROI values were closest to the mean values across the simulation was selected as a representative case and presented in the study. This approach ensured that the presented results reflect the project's expected economic performance and are robust enough to withstand fluctuations in input parameters.

To quantify investment costs, the number of downtime events, and the overall cost structure of the mining business, the expert estimate method was applied. The data was obtained through consultations and questionnaires from three independent companies with extensive experience in mining engineering and the economy.

Subsequently, the data obtained was triangulated and validated to minimise subjective bias and ensure the utmost accuracy of the input data.

Despite the robust and comprehensive nature of the methodology used, it is essential to keep its limitations in mind. Although 150 simulated scenarios constitute a substantial sample, they may not fully capture all potential combinations and interactions among the variables affecting the project's economic efficiency. In addition, even when expert estimates of investment costs and operating parameters are triangulated and validated, they remain inherently subjective and may be inaccurate and biased. Another limitation is the DCF model itself, which relies on estimates of future market price development, operating expenses, and discount rates that may differ from the actual values. The simulation primarily quantifies the economic impacts of innovations. It does not include entirely qualitative aspects, such as organisational changes, resistance to change, and the social effects of the implemented technology.

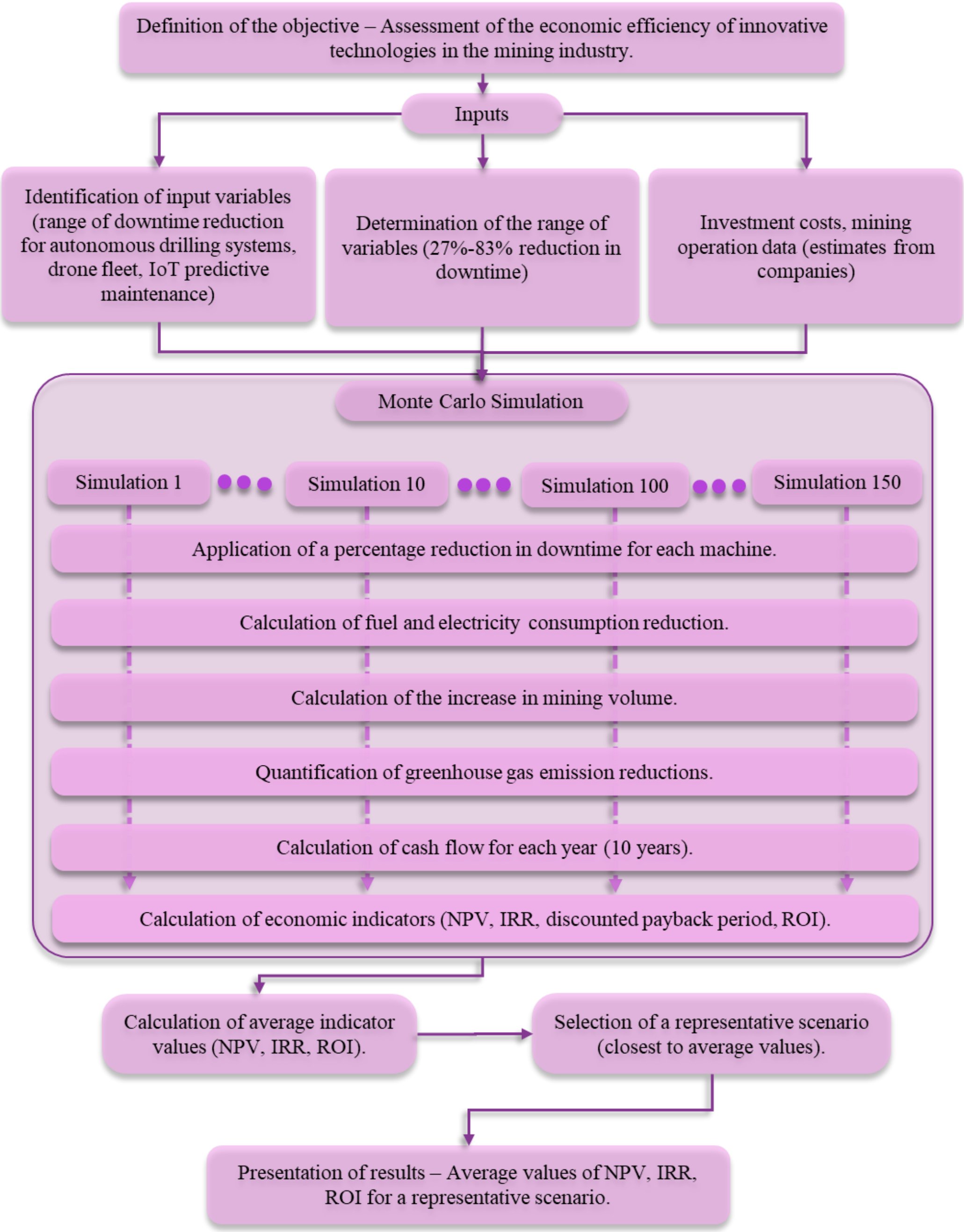


Fig. 1. Research methodology process. Source: authors' own work

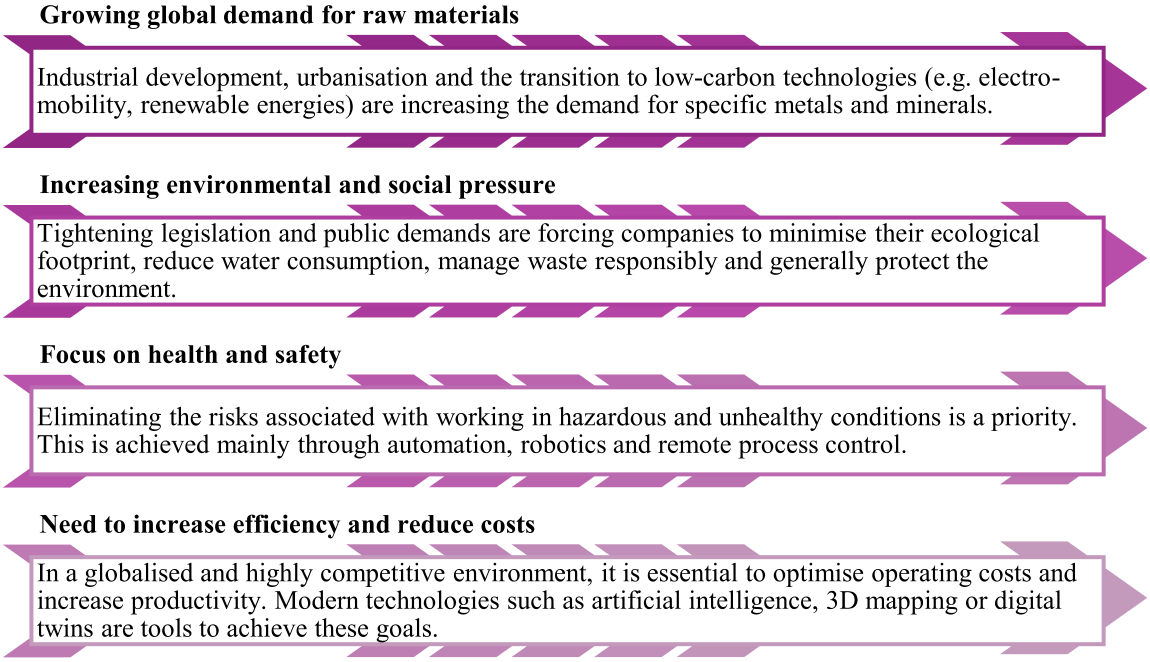
Finally, a regression analysis was conducted to quantify the dependence of the individual economic indicators (NPV, IRR, discounted payback period, ROI) on the reduction in downtime events achieved in the simulated scenarios. Using this analysis, we were able to identify the intensity and direction of the correlation between reductions in downtime and the project's economic efficiency, as well as determine which innovative technologies have the most profound impact on improving economic indicators. The results of the regression analysis were used to validate the model and to assess the sensitivity of the economic indicators to changes in the extent of downtime reduction.

Solution

Motivation and Importance of Innovation in the Mining Industry

The implementation of innovative technologies in the mining industry presents a complex challenge, significantly affecting technologies, processes, economy and marketing strategies. The systematic analysis of the relationships among these components is essential to establishing a competitive, socially responsible industry. The integration of innovations is a key factor in achieving higher productivity, improving security levels, minimising environmental impacts, and building a positive image in society.

The mining industry faces significant challenges that require a fundamental transformation. Factors such as the declining quality and availability of deposits of non-renewable resources, along with increasingly stringent environmental regulations, make traditional mining methods unsustainable. In this context, innovation is becoming a prerequisite for survival and long-term prosperity in the industry.



Growing global demand for raw materials

Industrial development, urbanisation and the transition to low-carbon technologies (e.g. electromobility, renewable energies) are increasing the demand for specific metals and minerals.

Increasing environmental and social pressure

Tightening legislation and public demands are forcing companies to minimise their ecological footprint, reduce water consumption, manage waste responsibly and generally protect the environment.

Focus on health and safety

Eliminating the risks associated with working in hazardous and unhealthy conditions is a priority. This is achieved mainly through automation, robotics and remote process control.

Need to increase efficiency and reduce costs

In a globalised and highly competitive environment, it is essential to optimise operating costs and increase productivity. Modern technologies such as artificial intelligence, 3D mapping or digital twins are tools to achieve these goals.

Fig. 2. Key factors of changes in the mining industry. Source: authors' own work

The analysis of innovations in the mining industry focused on three fundamental aspects: the implementation of innovative technology, the optimisation of existing processing, and the achievement of measurable economic efficiency. The synergy between these elements and their contributions to more efficient and competitive mineral extraction were also investigated. Special emphasis was placed on the mutual link between technological innovations and the process of making processes more effective, which together resulted in a quantifiable improvement in operational cost-efficiency.

Innovative technologies, including automation, artificial intelligence, and advanced sensory systems, were a fundamental pillar of the mining industry's modernisation. That said, their practical implementation required substantial adjustments to existing operating processes. The process optimisation involved making work processes more efficient, minimising downtime, and reducing resource consumption, thereby maximising the impact of the newly implemented technologies.

The primary purpose of integrating innovations was to achieve provable economic efficiency, measured using specific economic indicators: net present value (NPV), internal rate of return (IRR), return on investment (ROI), and payback period. The analysis of these indicators in the context of investment in new technologies and processes was crucial for making strategic decisions and successfully implementing innovations across the industry.

Simulation Analysis of the Economic Efficiency of Innovations

As part of the analysis of innovations in the mining industry, focusing on technologies, processes, and economic efficiency, we conducted an investment decision simulation. The simulation served as a practical tool for quantifying the economic benefits of innovations and their impact on the financial performance of mining projects. The aim was to provide a realistic estimate of the potential returns and risks associated with implementing new technologies and optimising processes.

The simulation was based on modelling diverse scenarios and relevant parameters affecting the economic efficiency of mining operations. It accounted for capital expenditures (CAPEX), operational expenditures (OPEX), production quotas, market prices of non-renewable resources, and other relevant exogenous and endogenous factors. The basic input indicator and data point were the reduction, or rather the percentage reduction, in machine downtime and its inefficient use. Based on the analysis of three selected innovations – autonomous drilling systems (AI), a drone fleet equipped with LiDAR and software, and IoT-based predictive maintenance with a digital twin – the interval for downtime reduction was established at 27-83 per cent. The definition of this range was based on a combination of theoretical assumptions, internal analyses, and consultations with experts in the mining industry and relevant technological sectors. Such a wide range was chosen because there is no direct, publicly available data on the implementation of these technologies under identical mining conditions.

The lower end of the interval (27%) for autonomous drilling systems reflects the minimum estimated improvement from eliminating human error and process standardisation. This level of improvement is expected even under less-than-ideal conditions for technology implementation. The upper limit (83%) represents the potential of these systems under complete optimisation of the drilling process and the use of advanced analytical tools.

In a drone fleet equipped with LiDAR and software, LiDAR-equipped drones improve data accuracy and speed information collection. The lower limit of the downtime-reduction interval accounts for limitations imposed by weather conditions and legislation. In contrast, the upper limit reflects the potential for substantial improvement in planning and the prevention of unexpected events.

For the IoT-based predictive maintenance and digital twin, the lower interval limit accounts for implementation and system integration costs and assumes that the system can identify at least part of potential malfunctions. The upper limit reflects the potential to minimise unplanned downtime through malfunction prediction and maintenance optimisation, but it still acknowledges that it is impossible to predict all types of malfunctions.

For the relevant evaluation, 150 scenarios were simulated to account for the variability and complexity of the impact of individual innovations on overall efficiency. Through the simulation, we sought to account for the uncertainty and variability in implementing new technologies and quantify the potential magnitude of economic benefits in the mining industry.

The simulation results served as the basis for strategic decision-making and ex-post evaluation of the efficiency of the implemented innovations. By comparing different investment variants and technological solutions, we identified the alternatives that would be most beneficial for maximising profit and mitigating risks in the mining industry. The simulation also allowed us to analyse the sensitivity of key indicators to variations in key parameters, which contributed to a deeper understanding of potential impacts and to the design of more robust investment strategies in response to dynamic changes in the market environment.

Quantification of the Impact of Downtime Reduction using the Monte Carlo Simulation

The Monte Carlo method with 150 simulations enabled us to quantify the impact of reducing machine downtime on key economic indicators, accounting for the influence of other variables, including fluctuations in non-renewable resource market prices, energy expenditures, and seasonal deviations in production capacity. We are focusing on the analysis of the correlations between downtime reduction and three economic indicators: return on investment (ROI), internal rate of return (IRR) and net present value (NPV).

The simulation results show a positive correlation between the percentage reduction in downtime and ROI. The graph clearly shows that the greater the reduction in downtime, the higher the return on investment. The determination coefficient ($R^2 = 0.3287$) suggests that approximately 33% of the variability in ROI may be explained by changes in downtime reduction. The remaining variability is due to other factors, underscoring the economic model's complexity.

As with ROI, a positive correlation between IRR and downtime reduction was also observed. Higher downtime reduction generally leads to a higher IRR. The correlation strength, as measured by R^2 (0.3086), is comparable to ROI, indicating that downtime reduction accounts for approximately 31% of IRR variability.

The simulation demonstrates that NPV correlates most strongly with downtime reduction. Reducing downtime increases NPV. The determination coefficient R^2 (0.3287) indicates that downtime reduction accounts for approximately 33% of the variability in NPV. Higher downtime reduction also directly increases cash flow, ultimately increasing the project's total present value.

The simulation clearly demonstrates that downtime reduction has a statistically significant positive impact on ROI, IRR, and NPV. Investing in technologies and processes that reduce machine downtime has demonstrable benefits for improving economic indicators. It should be noted that the other modelled variables (market prices, expenditures, external events) also affect the resulting values and should be considered when making strategic investment decisions.

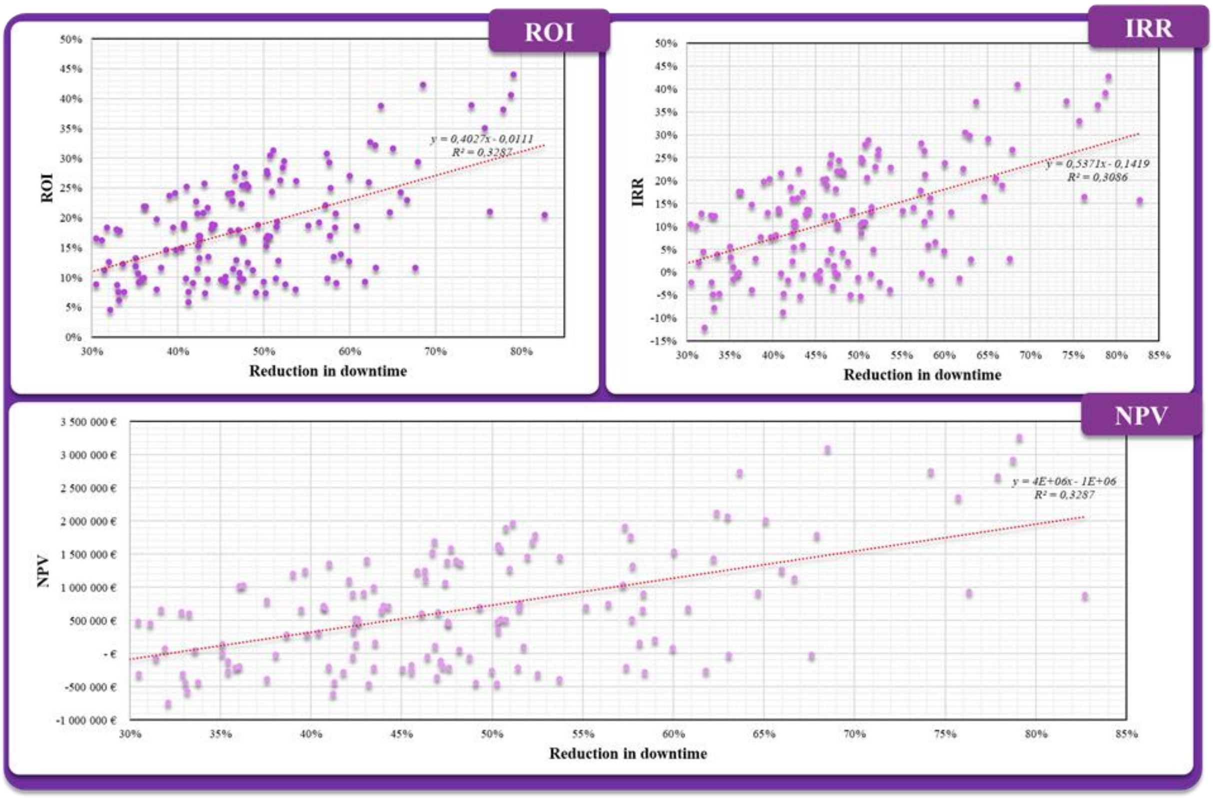


Fig. 3. Correlation between economic indicators and downtime reduction. Source: authors' own work

Representative Scenario Analysis: Model with Average Economic Efficiency Values.

One of the models was examined more closely to provide a deeper analysis of the economic impacts and potential benefits of innovations. The model was selected from the total number of simulations based on its proximity to the average values of key economic efficiency indicators (ROI, IRR, NPV). The model analysis allowed us to better understand how downtime reduction and other variables affect the financial performance of a project under conditions closely resembling the expected average results.

The analysis shows a significant decrease of monthly downtime in 2026 versus 2025 (from 902.27 h to 486.60 h), which is an absolute decrease by 416.37 h and a relative reduction of approximately 46% in the individual months, with the greatest decreasing in the period from March to June (e.g. March 2025: 74.95 h vs 2026: 49.81 h; April 2025: 71.38 h vs 2026: 28.01 h), April to June show the most significant reductions, with 2026 having lower downtime in all months, suggesting more effective maintenance and operating practices, better planning and potential related decrease of energy consumption.

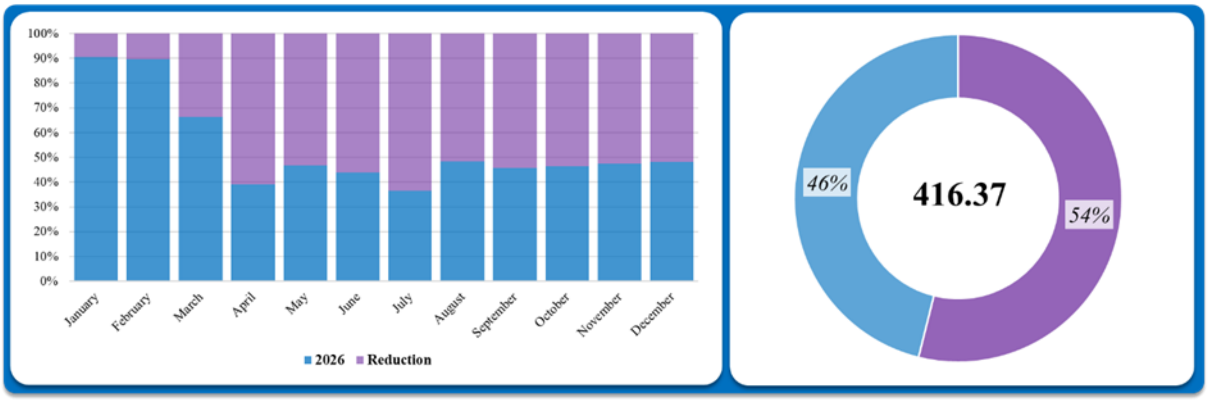


Fig. 4. Year-on-year comparison of downtime reduction (2026 vs 2025). Source: authors' own work

The graphic comparison (Figure 4) illustrates that machine energy consumption decreased in 2026 compared with 2025, leading to a significant, seasonally varied reduction, among other factors. Electricity costs decrease by 8.51% in January up to the maximum of 18.70% in December, with the most remarkable increase in the reduction taking place in the second half of the year; fuel exhibits a similar trend (7.06% in January up to 15.95% in December), peaking in November at 17.66%. The results suggest that the implemented measures are efficient throughout the year, with seasonal fluctuations reflecting variations in operating conditions, machine usage intensity, and the related reduction in downtime.

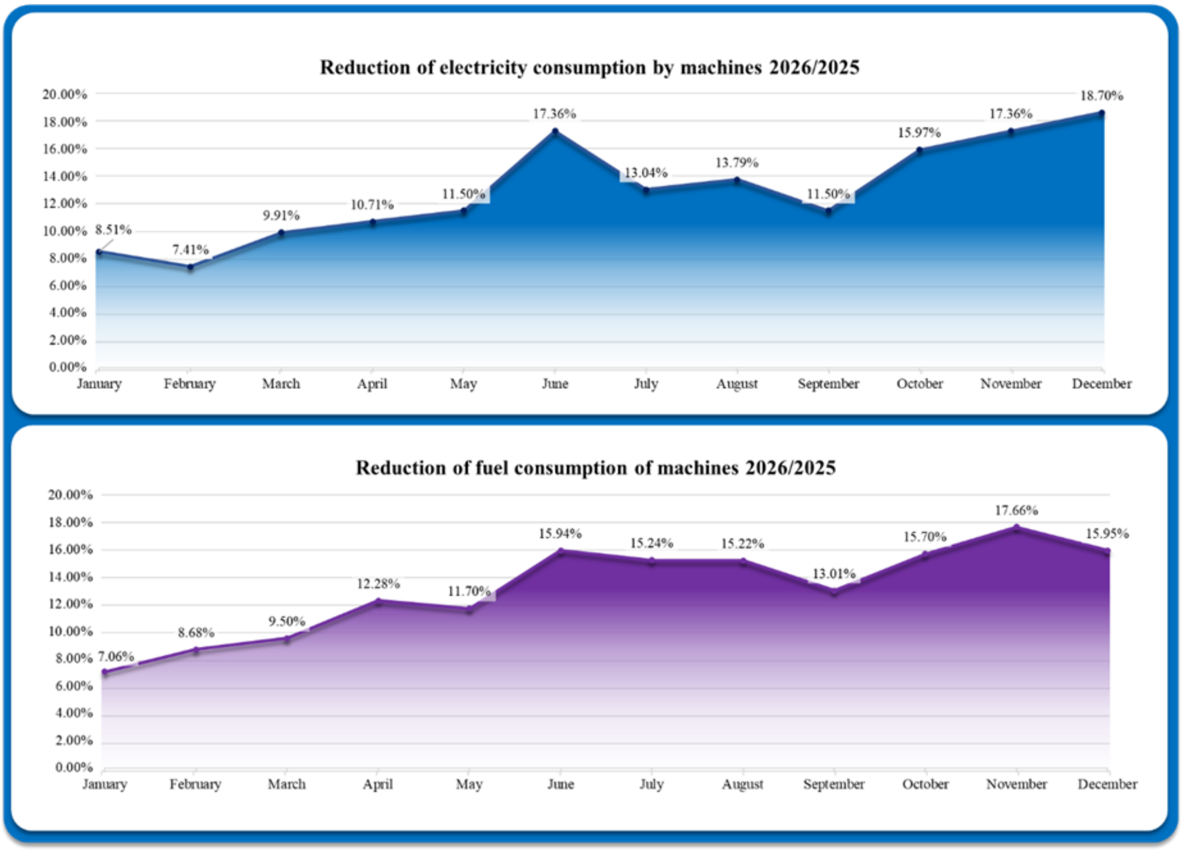


Fig. 5. Year-on-year reduction of electricity and fuel consumption (2026 vs 2025). Source: authors' own work

The analysis shows a continued increase in mining activity between 2026 and 2025. The absolute increase in the individual months ranges from 835.13t in January up to 11,427.04t in June, with the total annual absolute increase being 67,318.56t. The relative monthly increase ranges from 3.20% to 17.60%, with a mean annual increase of around 13.46%, indicating a steady monthly increase in production.

The total recorded increase in revenues was €470,986.26, representing a relative increase of 13.44%. The highest monthly revenue increase occurred in the period from June to August, with the annual trend continuing to rise. These indicators demonstrate that more extensive mining is associated with substantial increases in revenue and a positive impact on overall profitability, even though we focus on absolute and relative increases rather than on year-on-year total volume.

The simulation accounted for the fact that the innovations would have to be installed during the first two months (January and February), which explains the lower percentage increase during these months. It also explains the lower absolute and relative increases in the first two months compared to the remaining months, when the innovations are fully functional, and the production (in tonnes) and revenues increase more substantially. The trend continues throughout the year and peaks in the following months, with total year-on-year values remaining in line with the indicated absolute and relative increases.

Fig. 6. Year-on-year comparison of mining activity and revenues (2026 vs 2025). Source: authors' own work.

The economic analysis of investing in innovations aims to quantify the efficiency of resources invested in autonomous drilling systems (AI), drone fleets equipped with LiDAR and software, and IoT-based predictive maintenance using a digital twin. Its objective is to evaluate time-distributed cash flows, discounted to present value (NPV), internal rate of return (IRR), and return on investment (ROI).

The model used includes initial investment costs (€1,205,000) and cash flow projections over the prediction period, with the discount factor applied. Cash flow discounting is carried out by applying a discount factor to future cash flows.

The analysis results indicate an internal rate of return (IRR) of 11.43%, indicating that the project exceeds alternative capital expenditures. The net present value (NPV) is €552,117.27, indicating positive value creation. Furthermore, the return on investment (ROI) of 17.29% suggests an efficient use of the invested funds.

It should also be noted that the project's discounted payback period is 7.4 years. However, the results are sensitive to changes in the discount and inflation parameters, as well as to the early implementation period, resulting in a negative cumulative cash flow. The positive transition to positive values confirms the improvement in the financial profile. Risks to the project include technical delays and changes to the price range, which may affect its implementation.

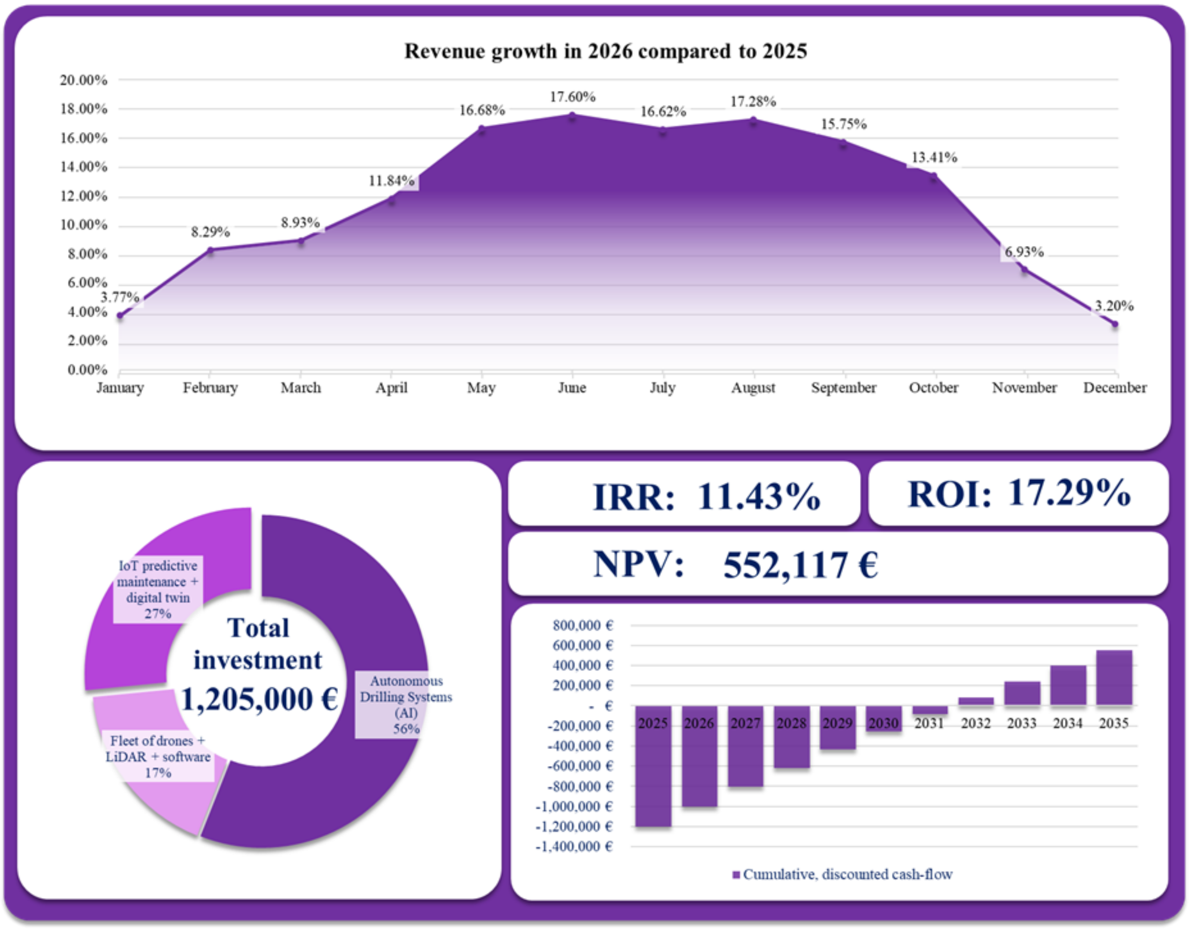


Fig. 7. Financial return on investment in innovations. Source: authors' own work

The implementation of innovative technologies enables the mining industry to achieve two goals: increasing economic efficiency and improving environmental sustainability. Specifically, the reduction in emissions of 201,405.13 kg CO_2, with the predominance of CO_2 in the total volume of emissions saved (99.65%), hints at the successful decarbonisation of the energy and transport processes in the field. This highlights the importance of transitioning to low-carbon technologies and fuels.

Simultaneously, the fact that the remaining 0.35% of emissions are attributed to particulate matter (PM), sulphur dioxide (SO_2), nitrous oxides (NOx) and carbon monoxide (CO) reminds us that environmental risks are not limited to greenhouse gas emissions. Effective management and reducing these "typical" pollutants remain crucial to minimising the negative impact of mining operations on air quality and public health.

Historically, petrol has been the most significant contributor to pollution, as evidenced by the effectiveness of the technological portfolio transformation towards the low-carbon economy. The transition to alternative energy sources, including electric vehicles, hydrogen, and organic fuels, along with investments in energy-efficient technologies, results in measurable reductions in emissions and improvements in the environmental profiles of mining companies.

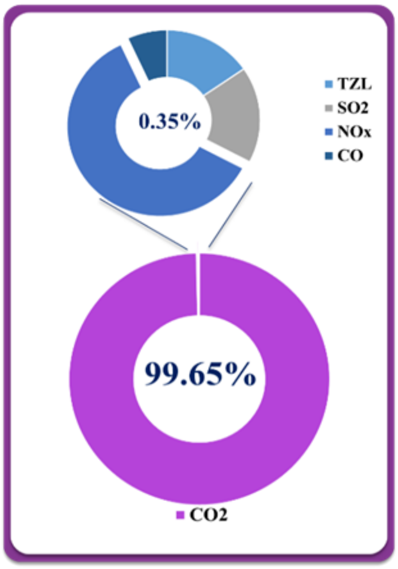


Fig. 8. Reduction in air emissions with the use of innovations. Source: authors' own work

Discussion

The study's results confirm that innovations play a key role in the survival and prosperity of the mining industry, in line with Balci and Kumral (2022). The economic efficiency of innovations (increases in revenues, ROI, IRR, NPV) aligns with the findings of Fan et al. (2017) and Sánchez and Hartlieb (2020) on the positive impact of innovations on economic growth and efficiency. Similarly, our findings on machine downtime reduction and increased mining volume support the argument of Warhurst and Bridge (1996) regarding productivity improvements through innovation. Specifically, simulations of autonomous drilling systems (AI) and drones equipped with LiDAR, along with IoT-based predictive maintenance, confirm the positive impact of these technologies on the efficiency of mining operations. In addition, our findings regarding the decrease in energy consumption and CO_2 emissions are consistent with those of Ranose et al. (2020) and Jovanovic et al. (2023), who emphasise the importance of process innovations for environmental sustainability. And finally, the Monte Carlo simulation using 150 scenarios and sensitivity analysis substantiated the importance of innovation management tools for the successful implementation of new technologies, as stated by Varava and Kovalchuk [8]. Both environmental and external factors may affect innovations, including market price fluctuations of non-renewable resources, changes in tax legislation, energy costs, seasonal deviations in the production capacity and external factors, such as late deliveries, which corresponds to the work of Menghetti (2005), Nicolas et al. (2020) and Daly et al. (2021) about the importance of adjusting to the market situation and challenges that the mining industry is facing. On the other hand, our findings of significant improvements in economic efficiency and environmental sustainability contrast with those of Zhang et al. (2014), which report low innovation efficiency in the traditional mining sector. This disparity may stem from the fact that our simulation focuses on specific technologies and processes with proven impact on efficiency. In contrast, Zhang et al. (2014) investigated a broader innovation ecosystem in the mining industry. Our findings on technologies that yield significant productivity and efficiency gains contradict Bartos (2007), who describes the mining industry as low-productivity relative to high-tech industries. Our simulation demonstrated that current approaches and investments in technology may help the sector achieve higher productivity standards.

Although our study was extensive in scope, there are certain limitations worth noting. Despite our efforts to consider a wide range of internal and external factors in the simulations, many variables that could significantly affect the economic efficiency of the mining business were not fully incorporated into the model. These include, among others, accurate geological deposit characteristics, which may affect mining costs; unexpected changes in the regulatory environment, which may lead to higher regulatory compliance costs; and global supply chain fluctuations, which may impact the availability and prices of input materials and technologies. Another limitation is that the simulation relied on assumptions and estimates that may not accurately reflect actual operating conditions. This is why it is necessary to interpret the results carefully and consider the potential impact of unexpected events and modelling inaccuracies.

This simulation-based analysis is a valuable tool for mining companies, as it allows them to quantify the economic benefits of innovations. This supports the process of making informed, strategic decisions about investing in new technologies and optimising their implementation in practice.

Future research should aim to gain a deeper understanding of the factors affecting the success of implementing innovations. It should focus on organisational culture and management style (building on Kashan et al. (2021) and Vargas and Lorenzo (2024)) to understand how these factors foster an innovative environment. It is equally important to examine the impact of specific contextual factors, such as geological conditions and the regulatory environment, on innovation efficiency across various mining sites (building on Reshetilova and Nikolayeva (2011) and Daly et al. (2021)).

Another step should be developing more complex models to evaluate the environmental and social impacts of innovations in the mining industry. It is necessary to build on the work of Jovanovic et al. (2023) and Adomako and Nguyen (2023), and to account for the broader sustainability context. Finally, the analysis of the role of strategic partnerships and collaboration with technology suppliers (inspired by Yudhya (2018) and Ananeh-Frempong (2022)) may reveal new opportunities to accelerate innovations in the mining sector and maximise their overall benefits.

Conclusions

The study examined the economic efficiency of innovations in the mining industry through a Monte Carlo simulation, considering various scenarios and variables that affect the financial performance of mining projects. It focused on quantifying the impact of reducing machine downtime achieved by implementing autonomous drilling systems (AI), a fleet of drones equipped with LiDAR technology and software, and IoT-based predictive maintenance using a digital twin on key economic indicators, such as ROI, IRR, and NPV.

The simulation results showed a positive correlation between downtime reduction and improvements in economic indicators, with the most significant impact on NPV. The representative scenario analysis, which accounted for average economic efficiency values, confirmed significant reductions in monthly downtime, energy consumption, and CO_2 emissions, along with increases in mining volume and revenues. These findings hint at the synergistic effect of the implemented innovations, which not only improve economic efficiency but also contribute to the environmental sustainability of mining operations.

Our results support the claim that investments in technologies and processing aimed at reducing non-productive machine downtime are relevant to improving economic indicators and are consistent with the existing literature on the positive impact of innovations on economic growth and efficiency in the mining industry. Despite the above, it remains necessary to account for the financial model's complexity and the impact of other variables, such as market prices, costs, and external events, in strategic investment decisions.

To conclude, this simulation-based analysis provides a valuable tool for mining companies, allowing them to quantify the economic benefits of innovations and support strategic investment decisions in recent technologies. Further research should focus on a more in-depth analysis of the impact of organisational, contextual, and environmental factors, such as the role of strategic partnerships in the successful implementation of innovations in mining companies.

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