DEVELOPED IN CHILE:

High Impact

Research that introduces a new paradigm in the management of geological uncertainty

With the participation of both industry and academia, this work proposes a way of understand-ing this variable in the mining sector, with direct applications to world-class projects.

In August 2025, the journal Minerals published the article *"A Stochastic Framework for Mineral Resource Uncertainty Quantification Management at Compañía Minera Doña Inés de Collahuasi"*, developed by academics from the Department of Mining Engineering at the University of Chile, Alejandro Cáceres Saavedra and Xavier Emery, in collaboration with Compañía Minera Doña Inés de Collahuasi and GeoInnova a company cofounded by Cáceres, who has served as its R&D manager for 15 years. The impact was immediate: over 15,000 downloads within the first few days, ranking as the most accessed publication since 2023, and sparking a global discus-sion among experts in geosciences, mine planning, and finance. The_reason? The study introduces a new approach to understanding and managing geological uncertainty in mining, with direct applications to world-class projects. Cáceres explains that he chose to conduct this research as part of his Ph.D. in Mining Engineering at the University_of_Chile—rather than at other leading mining school worldwide because of the program's openness to new ideas and the opportunity to work alongside a world-class research team. This combination of academic rigor, interdisciplinarity, and strong industry ties enabled him to connect his professional experience with a scientific platform capable of advancing cutting edge methodologies for the mining sector.

The Challenge: Bridging the Gap Between Expectations and Outcomes

One of the mining industry's most persistent issues is the systematic gap between what is planned and what is actually produced. Higher costs, execution delays, and lower head grades are all-symptoms of a common root cause: unmanaged geological uncertainty. The article highlights that the industry has traditionally relied on deterministic methodologies—such as single block models and confidence classification based on-drillhole spacing—that rarely communicate the magnitude of risk in an explicit way. This leads to false certainties and inflated expectations, both for investors and for operators themselves.

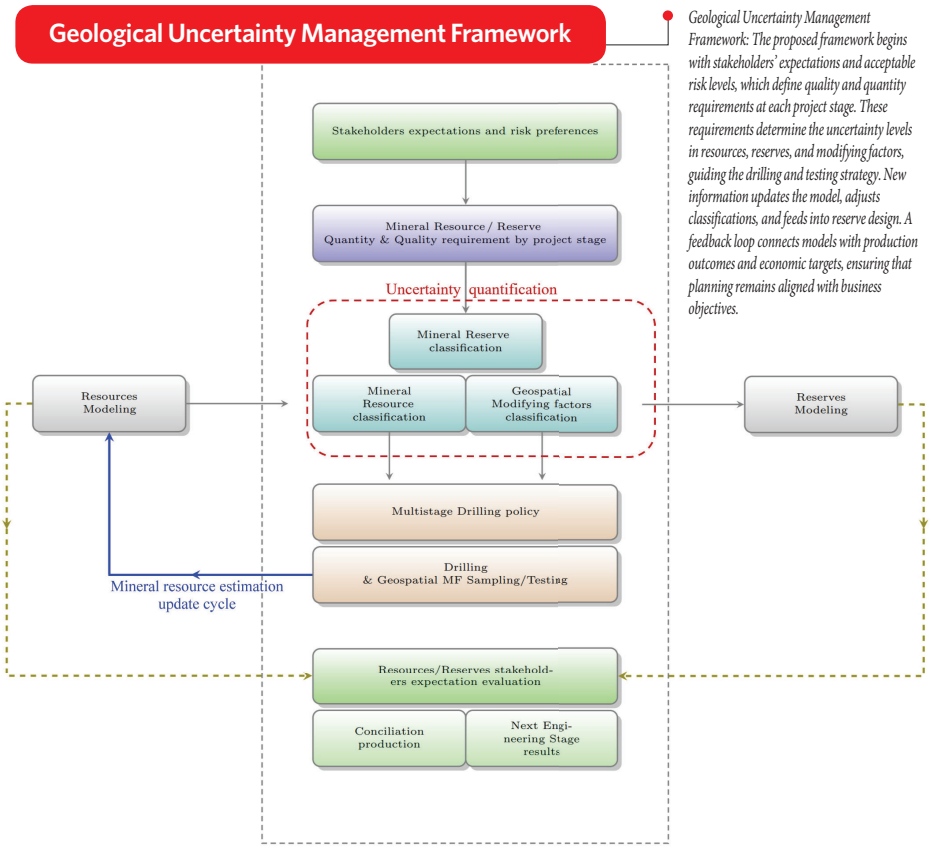
The Methodological Contribution: From Geology to Finance

The work presented integrates geostatistical simulations to quantify-both spatial uncertainty (in geology and grades) and its propagation-through time in the cash flows associated with a mine plan. One key finding is that spatial correlations in-geology and in the modifying factors-used to convert mineral resources-into mineral reserves result in temporal correlations in cash flows. In-other words, geological uncertainties travel through the mine plan-and generate uncertainty in future-revenues.

Drilling As A Strategic Investment

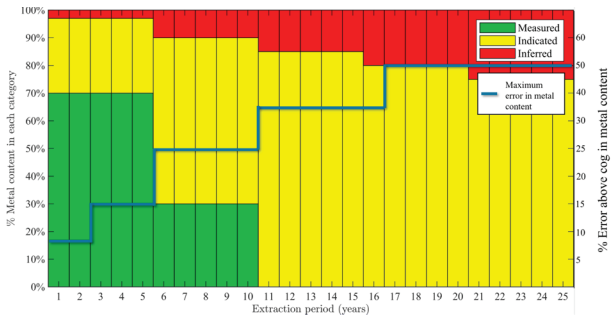
The standard practice in mining has been to drill to meet proportions of Measured or Indicated resources, following corporate guidelines or reporting codes, and-treating drilling primarily as a cost. This research challenges that approach:-it proposes viewing drilling as a strategic investment in risk reduction, on-par with mine planning.

Using optimization algorithms, it identifies which deposit areas yield the greatest reduction in NPV uncertainty per meter drilled, ensuring stronger financial stability for the project. The results are compelling: with less drilling investment.



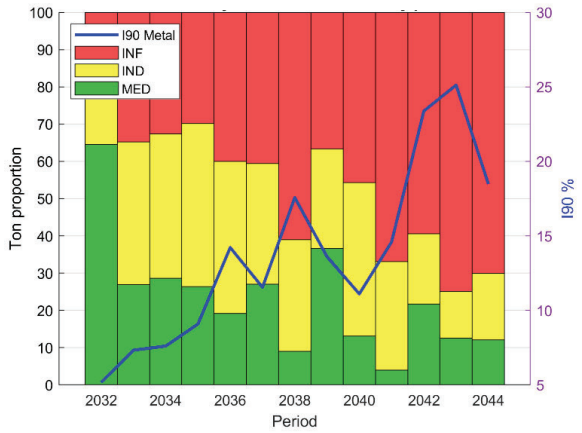
Geological Uncertainty Management Framework: The proposed framework begins with stakeholders' expectations and acceptable risk levels, which define quality and quantity requirements at each project stage. These requirements determine the uncertainty levels in resources, reserves, and modifying factors, guiding the drilling and testing strategy. New information updates the model, adjusts classifications, and feeds into reserve design. A feedback loop connects models with production outcomes and economic targets, ensuring that planning remains aligned with business objectives.

Resource Sustainability Matrix - Quantity and Quality profile



Proposed Sustainability Matrix Format. For each project stage, the matrix defines the required proportion of confidence categories and the maximum allowable annual uncertainty, for example, in metal content. By displaying the total uncertainty composition per year, the matrix transforms uncertainty reduction into an explicit objective of project development.

Sustainability Matrix and I90 Metal by period



The sustainability matrix applied to a mine plan shows the proportion of each resource category and the annual uncertainty level based on the information available from existing drill holes. It allows uncertainty reduction to become an explicit objective within project development

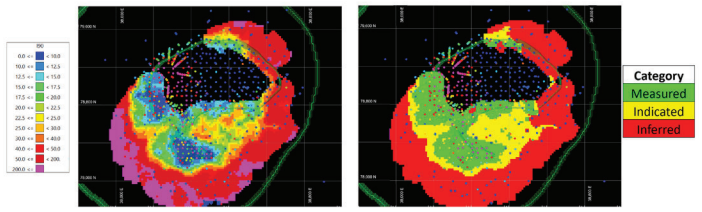
This approach achieves greater risk reduction than traditional regular grid designs.

Uncertainty: From Local Scale to the-Mineral Resource Statement.

This work introduces local uncertainty metrics using simulated scenarios of the mineral deposit, to directly classify mineral resources into Measured, Indicated, and Inferred categories, facilitating communication and understanding of their significance. Additionally, it revisits the sustainability matrix developed at Codelco in 2004, adding a dimension of uncertainty level in the mine plan for relevant variables such as contained metal. Essentially, it presents the amount of high-confidence resources and the quality of that confidence, using objective metrics of associated uncertainty per year in the mine plan. This transforms classification into a strategic communication tool for board members, banks, and investors who can now clearly see how much risk exists and how well it is managed.

Compañía Minera Doña Inés de Collahuasi: Leading the Management of Geological Uncertainty

What stands out most is that this research goes beyond theory. Compañía Minera Doña_Inés de Collahuasi, under the leadership of Andrés Pérez, Manager of Mineral_Resources and Development, spearheaded its implementation with a team that includes geology.



An uncertainty map of local metal content uses cool colors to represent lower uncertainty and warm colors to indicate higher uncertainty. These maps serve as the basis for defining mineral resource classification. The direct use of uncertainty metrics provides greater transparency regarding the meaning of each resource category for different stakeholders.

Mine planning and geotechnics, with a more integrated business vision, support the development and implementation of the approach in their mega-deposits. The results already include:

- Comprehensive geostatistical simulations of geology and grade
- Optimized drilling campaigns
- Classification supported by uncertainty based metrics
- Regular integration into your modeling cycles

Jorge Pérez, Superintendent of Mineral Resources, and Felipe Ibarra, Senior Geologist and QP at CMDIC, explain that this development was enabled by the vision behind Collahuasi's risk management policy, the strong technical skills of its teams, mining executives with advanced training in both technical and business management, and the support of academics and specialized firms that helped materialize the process. The authors highlight that these ideas emerged in a unique context: over the past 25 years, the region has raised its educational standards, built programs of excellence, exported academics to universities in the UK, Canada, and Australia, and trained professionals who now hold technical and executive roles in world-class companies. Cáceres emphasizes the region's mining tradition and the adoption of world-class practices, supported by contributions from key figures such as Edmundo Tulcanaza, Pedro Carrasco Castelli, Diniz_Ribeiro, Eduardo Contreras M., Alfredo Marín, and Marco.

Building on Alfaro's foundational work, new methodologies are emerging today. Against this backdrop—combined with the region's exceptional geological richness—it is clear that Chile, Brazil, and Peru lead several of the most relevant advances in global mining.

Implications For Global Mining

The article calls for a cultural shift: from quantity to quality, from geometry to explicit uncertainty, from drilling as an expense to drilling as a value-driven investment.

Its authors note that this proposal could become the foundation for new practices enabling more efficient mining business development, and eventually a new international standard. Gonzalo Fuster, QP at CMDIC and board member of the Mining Resources and Reserves Competency Commission, emphasizes that this work anticipates the necessary evolution of reporting codes and the growing demands of financial markets, ultimately driving a more sustainable mining industry with reduced risk for investors.

As they aptly summarize: "Uncertainty does not disappear; it is managed." Doing so transparently is the only way for mining to deliver on its value promises.

The article is open access and can be read__at_the_Minerals_journal_link: **https://www.mdpi.com/2075-163X/15/8/855.**