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The economics of mine waste reduction: The case of ore-sand

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HIGHLIGHTS

- We analyze the economic incentives for mining companies to reduce tailings by adopting large-volume sand by-products.
- We develop an economic model to quantify these effects using an iron-ore operation as a case study.
- Our model captures the main drivers of profitability of the operation and its response to various sources of uncertainty.
- Our results demonstrate substantial profitability in adoption, though significant heterogeneity exists across scenarios.
- Cost savings in tailings waste management and mine rehabilitation from the primary operation provide robust economic incentives for adoption.

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ABSTRACT

Amid rising mineral demand for the renewable energy transition and a long-term decline in average metal ore grades, volumes of mine waste are expected to increase significantly. This paper presents an economic model to assess the private economic benefits of extracting large-volume by-products to reduce mine waste. Using the case of ore-sand, a type of manufactured sand that can be produced as a by-product of metal ore mining, this paper quantifies profitability across various adoption scenarios. The dynamic economic model is calibrated to a representative large-scale iron-ore operation covering a 30-year mine life and uses Monte Carlo simulations to evaluate the different adoption scenarios. Under conservative assumptions, the simulations indicate significant economic incentives for ore-sand adoption though with substantial heterogeneity across factors such as the costs of waste management and rehabilitation, recovery rates, processing efficiency, and output prices. The findings highlight that, while ore-sand profitability is subject to important uncertainty in costs and final demand, cost savings in tailings management and mine rehabilitation from the primary operation can provide robust economic incentives for adoption. The findings do not explicitly model potential improvements in primary production which may result from tailings reduction when production is constrained by tailings transport and storage capacity, an effect that could further increase profitability suggesting our results may be interpreted as a lower bound.

1. Introduction

Increasing demand for minerals, driven in part by the green energy transition (Elshkaki et al., 2018; Hund et al., 2020), alongside the long-term decline in metal ore-grades (Mudd, 2007; Priester et al., 2019), has led to significant growth in mine waste, including tailings (Valenta et al., 2023). Tailings and their management present both acute and chronic risks to the environment and local communities near extraction sites (Franks et al., 2021; Hudson-Edwards et al., 2024). Recognizing these challenges, there is growing awareness of the need to

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adopt cleaner production technologies and techniques, and responsible mine waste, mine closure and rehabilitation management (Edraki et al., 2014; Measham et al., 2024). These practices, especially if they can be implemented from the mine design phase, could lead to significant reductions in the mining footprint (Valenta et al., 2023; Tang and Werner, 2023).

This study investigated the economic incentives for adding secondary processing circuits to extract previously unused silicate mineral by-products, thereby effectively reducing tailings waste production, and the associated management, closure and rehabilitation costs. For this purpose, an economic model was developed to quantify the private economic benefits from the production of manufactured sand from the unutilized silicate minerals of the metal ore, hereafter referred to as ore-sand (Franks et al., 2025; Segura-Salazar and Franks, 2023a,b; Golev et al., 2022).[1] Production of ore-sand as a 'secondary product' or 'by-product' ,[2] aligns with waste reduction, cleaner production and circular economy principles promoted in the industry (Kinnunen and Kaksonen, 2019; ICMM, 2024).

The model was calibrated to resemble a large-scale iron ore operation based on S&P Global data from Vale's Brucutu mine covering the period between 1994 and 2013, along with technical inputs and operational insights from its ore-sand production branch, Agera, where ore-sand production was pioneered and is currently (in 2025) in production at commercial scale (Golev et al., 2022; Vale, 2022, 2023; Nogueira, 2023, 2024). The innovation was partly motivated by the 2019 tailings storage facility failure at a similar iron ore mine (Córrego do Feijão) in Minas Gerais, Brazil. The model incorporates the main characteristics of a mining operation within a modelling structure that is general enough to be adapted to other types of similar waste reduction technologies, beyond the case of ore-sand. Model results were used to examine the profitability of implementing ore-sand technology in the face of shocks to revenue and costs, such as those induced by price volatility, recovery rates, and the costs associated with the processing of each commodity.

The model outcomes can be described in two main dimensions. The first is an extensive margin, which refers to the adoption decision determined by the fixed costs of introducing the technology of secondary production (in this case, ore-sand). These costs are likely to be offset by the reduction in tailings management, tailings storage, mine closure and rehabilitation costs resulting from the decreased mine waste. The second is an intensive margin, which refers to the relative size of the secondary operation and is determined by the marginal costs of the secondary commodity in relation to the primary commodity. Both dimensions are influenced by three main sources of revenue and cost uncertainty. The first is price volatility of the primary and secondary commodity; the second is the recovery rate, which affects the revenue productivity of each activity by varying the output of each commodity, and the third is the costs associated with the processing of each commodity.[3]

It is shown that the potential gains from adoption, although substantial, exhibit significant heterogeneity in the profitability across the various scenarios. This heterogeneity is primarily driven by the degree of reduction in waste management and rehabilitation costs. On average, simulations of the model indicate substantial gains of additional profits for the adoption scenario in comparison to a business-as-usual scenario for a life of mine of 30 years, provided that a minimum threshold of waste-related costs reductions is exceeded. Even when considering different uncertainties in costs and revenue on ore-sand production, the cost savings from reducing mine waste provide compelling economic incentives for adoption. These findings are derived without explicitly modelling potential improvements in primary production that are enabled by tailings reduction in circumstances where primary production is constrained by tailings storage capacity, an effect that could further increase the profitability of the adoption scenario.

This paper contributes to the literature in three important ways. First, it presents the first quantification of the profitability of adopting ore-sand, a novel cleaner production technology in the mining sector that has the potential to significantly reduce mine waste (Franks et al., 2025). Second, it develops and calibrates an economic model that captures the complexity of economic decision-making in medium-to large-scale mining operations, including the adoption of a production technology for mine waste reduction. Third, it integrates a circular economy perspective into an economic modelling framework. In a context in which the circular economy literature often lacks a quantitative structure that allows the consideration of the different channels and mechanisms that characterize economic modelling (Kinnunen et al., 2022; Valentine, 2024; Fullerton, 2024; Fevereiro et al., 2025). In this article, a circular economy strategy is evaluated through a quantitative economic model, contributing to the integration of circular economy principles into mainstream economic analysis.

The proposed modelling framework differs from others in related literature, such as real option evaluations (Dimitrakopoulos and Abdel Sabour, 2007; Savolainen, 2016; Rimélé et al., 2018, 2020), as it incorporates both a detailed cost structure and an explicit representation of the underlying production technology within the mine's optimization problem. By defining explicit functional forms characterizing these dimensions, this approach provides a deeper insight into the variables driving the decision-making processes of mining companies, in particular, that associated with mine waste. While it builds on existing work (see e.g., Cortazar et al., 2001; Packey, 2012; Asad and Dimitrakopoulos, 2013; Carneiro and Fourie, 2020; Burritt and Christ, 2021; Sulista et al., 2023), it introduces a simpler framework that can be generalized to similar production technologies while preserving modelling parsimony, thereby avoiding the complexity of models dealing with the optimal extraction paths (Haque et al., 2014; Thompson and Barr, 2014; Castillo and Dimitrakopoulos, 2014). It also lays the foundation for models that aim to understand how the recovery of critical minerals from mine tailings can affect the cost and revenue streams of mining operations (Araya et al., 2020).

[1] In Brazil, Vale has established a company, Agera, to market its ore-sand from Brucutu and other sites. We collected feedback from Agera to help calibrate the model and adjust the projected scale and profitability of ore-sand accordingly.

[2] Here, secondary production refers to a secondary product' that is not the primary product. These terms have similar meaning, with the term 'by-product'. Importantly, for the case of ore-sand, this 'secondary product' is not derived from the recycling or repurposing of mine waste; rather, it originates from minerals in the ore that would have otherwise been discarded or unused (Franks et al., 2025). For consistency, in this manuscript the term 'secondary product' was used to describe the ore-sand product that was produced alongside the primary pelletized iron oxide concentrate.

[3] Costs associated with catastrophic failure were not included in this paper; however, it is expected the risk of catastrophic failure would be reduce with a reduction in tailings production. This risk reduction component could be a significant driver in the decision to adopt ore-sand, given the large costs associated with tailings storage facilities and implications for mine rehabilitation (Armstrong et al., 2019a,b).

2. Background

Enormous volumes of waste material are produced by mining activities, more than in any other industry with an estimated 30 to 60 billion tonnes produced annually, making mine waste reduction and prevention a critical goal for sustainable resource extraction (Ndlovu et al., 2017;Golev et al., 2022; Franks et al., 2021). Efforts by industry to reduce the volumes of mine waste produced include pre-concentration and in-situ recovery, among others (Bian et al., 2012). However, opportunities remain for recovering currently unused-minerals from within mineral processing circuits in the form of aggregates, such as sand, which could be a profitable and preferable option for future mining operations, as it reduces the generation of mine tailings thus reducing requirements for subsequent disposal and treatment (Lottermoser, 2011; Suppes and Heus-Aßbichler, 2021; van der Ent et al., 2021; Sulista et al., 2023).[4] Ore-sand has properties similar to manufactured or processed sand and has the potential to be used in a wide range of applications, such as road sub-base, a fine aggregate in concrete, bricks, and glass (Mendes Protasio et al., 2021; Goulart Bezerra et al., 2021; Golev et al., 2022; UNEP, 2022; Valenta et al., 2023).[5]

Fig. 1 illustrates the key activities for a representative metal ore mine, including the option to produce ore-sand as a secondary commodity.

In early stages of production, the ore body is mined and ore-bearing rock is isolated from non-ore bearing rock and sent forward to the mineral processing plant. Within the mineral processing stage, the ore-bearing rock undergoes comminution (crushing, milling and screening) and beneficiation (segregation of ore minerals from non-ore minerals by gravity, flotation and other separation techniques). At the end of mineral processing an ore mineral concentrate is produced. In the case of iron ore this is a pelletized or sintered iron oxide concentrate, and the unwanted materials (effluents and crushed rock), which are known as tailings, are sent to a storage facility. With the addition of a secondary circuit for the recovery of ore-sand, minerals that would otherwise report to the tailings is recovered as a secondary commodity within the mineral processing facility. Both the primary and secondary commodities can undergo further processing in separate circuits in preparation for the final market. In the case of metals, this processing stage may also include smelting and refining.

Additional processing stages are needed to produce ore-sand as a secondary product. These are based on commercially available technologies, including separation of mineral particles according to their properties (e.g, flotation, magnetic separation, cycloning), dewatering, and product handling and transportation to consumer markets (Golev et al., 2022; Franks et al., 2025; Segura-Salazar and Franks, 2023a,b; Segura-Salazar et al., 2026). Ore-sands have shown improved characteristics compared to conventional sands. Their particle shape characteristics lie between those of manufactured sand and river sand, making them belong to a special manufactured sand (sub)category, with improved workability due to the artificial erosion caused by mineral processing circuits (Franks et al., 2025); in particular, due to the additional beneficiation stages (flotation, separation) that are not typically part of quarry processing plants.

Ultimately, the commercialization of the commodities determines the final profits, which depend on factors such as prices, taxes and subsidies, operational and fixed costs, initial investments and mine closure and rehabilitation costs.

Waste management, remediation, restoration, and mine rehabilitation can represent enormous costs for mining companies, especially if a major tailings storage facility failure occurs, during which mining operations often cease while the damage is repaired (Armstrong et al., 2019a,b). These costs may be further exacerbated by failure risks associated with climate change effects, such as heavy rainfall (Piciullo et al., 2022). Rehabilitation is crucial in some regulatory contexts where mining companies must deposit significant financial bonds as a guarantee for expected rehabilitation costs after closure, creating additional incentives for mining companies to reduce their environmental footprint by minimizing mine waste (Bowker and Chambers, 2015).

Last but not least, primary and secondary mining operations are subject to a high degree of uncertainty, as are the costs associated with tailings storage facilities and rehabilitation activities aimed at restoring mining sites (Armstrong et al., 2019a,b; Nassar et al., 2022). Price volatility, a feature of mineral commodities, is the literature's most extensively explored form of uncertainty (Brennan and Schwartz, 1985). Considering stochastic price shocks is vital as such shocks can make the adoption of secondary production viable during price booms, as the fixed costs of adoption may be recovered during these periods. In some cases, primary output may also be constrained by the capacity of tailings disposal and storage, which can be a key driver of secondary production adoption.

3. Methods

The methodology in this paper is divided into two. First, an economic model was developed that characterized a representative iron ore mining operation, from which analytical results were derived to investigate the economic incentives associated with the adoption of the production of a secondary commodity (ore-sand) that reduce mine tailings production. Second, the quantification of the economic effects of this adoption and the implications of various uncertainties related to adopting this secondary production technology were explored through simulation analysis. The sensitivity of these results was tested against key parameters in the model to provide evidence for the robustness of the economic potential for adoption in the industry.

3.1. The model

It was assumed that the present value of the yearly net cash flow is discounted at a rate ϑ for the life n of the mine. The yearly profitability π_{it} was determined by assuming the mining operation produced Q_{it} units of both a primary and a secondary commodity indexed by j, where secondary production was measured in equivalent units of the primary commodity. Then, the annual profits of an operation for a given year, aggregating over primary and secondary production, are given by:

$$\pi_{it} = p_{it} Q_{it} - C_{it} \quad (1)$$

where, for a given operation i at time t, $p_{it} = \tau_{it} p_t^o$, with $\tau_{it} \leq 1$, is a composite free-on-board price of the commodities (meaning the mine operation bore all transport costs up to a given point of final demand), τ_{it} is an inverse index of transport, processing, and waste management costs, p_t^o is the output market price, Q_{it} is the aggregate production of the mine measured in units of the primary commodity, and C_{it} represents the annual total costs. It was assumed that processing, transport, and waste

[4] It is recommended that a combination of different alternative (and often complementary) methods of mine waste reduction and prevention be used to achieve a more sustainable production structure in the industry (Franks et al., 2011; Edraki et al., 2014; Lèbre et al., 2017a; Valenta et al., 2023). These methods can be combined with application dependent on the types of commodities being mined (Valenta et al., 2023).

[5] There are differences in grading systems used to classify sand across countries. Australia, UK, and Brazil, for example, may have different standards to classify manufactured sand, as well as specific requirements for natural sand in construction applications. The American Society for Testing Materials (ASTM) provides a widely used classification system. A description of the Australian standards is presented in Segura-Salazar and Franks (2023a,b), where the authors recommend a new classification of grading requirements for different applications of ore-sand.

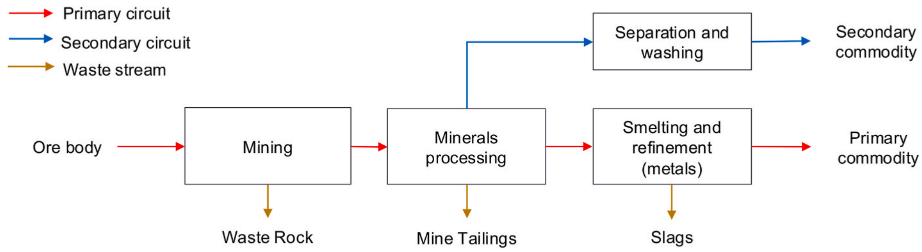

Fig. 1. Production stages in a metal ore mine operation with secondary production of ore-sand.
Notes: The figure illustrates the stages of production in a representative metal ore mine operation with secondary production circuit to reduce mine waste. Ore-deposits are mined, generating waste rock, and the extracted ore is processed. After mining, the ore minerals are processed, and the tailings waste remaining from this process is stored in tailings storage facilities. The primary and secondary commodity processing methods might differ depending on the products being mined. However, both processes share technological complementarities. Secondary commodity production reduces the waste material sent to tailings storage facilities, which translates into lower tailing risks, reducing failure likelihood, lowering mine closure and rehabilitation costs, and in some cases reducing production constraints on the primary commodity.

management costs follows the same 'iceberg' structure, meaning these costs are proportional to production, reducing revenue per unit produced.[6] Production was aggregated according to a Constant Elasticity of Substitution (CES) function given by

$$Q_{it} = \left(\sum_j \delta_j Q_{ijt}^{\rho}\right)^{1/\rho} \quad (2)$$

where δ_j is the intensity of production of each commodity j, and the parameter ρ governs the degree of substitution between primary and secondary production, with elasticity of substitution $\sigma \equiv \frac{1}{1-\rho}$. We assumed low substitutability in the production technology of the primary and secondary commodity, meaning that in the face of shocks to relative output prices the mine company adjust the production of each commodity, maintaining the same proportions associated to availability of resources (ore-reserves and unutilized materials from the primary commodity).

The total annual costs of the operation were $C_{it} = \sum_j c_{ijt} Q_{ijt} + \varphi_{it}$, where c_{ijt} denote the marginal cost of production of each commodity and φ_{it} the fixed costs. Fixed costs were decomposed into a component specific to each commodity (including upfront costs of the operation) and a component common to both primary and secondary production, as described by:

$$\varphi_i = \varphi_{Primary} + \varphi_{Secondary} + \varphi_{Rehabilitation} \quad (3)$$

For simplicity, mine closure and rehabilitation costs $\varphi_{Rehabilitation}$ were assumed to be known by the producer at the beginning of the operation, based on the total ore resources to be depleted. I.e., they are not endogenously determined over the life of the mine.

The two components capturing waste management and rehabilitation costs are described: 1) a fixed component that entered the cost function and considered the costs of mine closure and rehabilitation, and 2) a variable component that entered the profit function as a discount on revenue proportional to production. This distinction between fixed and variable components associated with mine waste is important for understanding the economic implications of mine waste reduction due to secondary production (Packey, 2012).

The production of each commodity was assumed to follow diminishing marginal returns with respect to labor, capital, and material inputs, following a Cobb-Douglas technology:

$$Q_{ijt} = \nu_j \epsilon_{ij} A_{ijt} K_{ijt}^{\alpha_j} L_{ijt}^{\beta_j} M_{ijt}^{\gamma_j} \quad (4)$$

where $\nu_j \equiv \left(\frac{1}{\alpha_j}\right)^{\alpha_j}\left(\frac{1}{\beta_j}\right)^{\beta_j}\left(\frac{1}{\gamma_j}\right)^{\gamma_j}$ is a normalization constant and ϵ_i is an idiosyncratic component specific to each mine. For a given operation i, and commodity $j \in \{primary, secondary\}$ in year t, A_{ijt} is the technology, K_{ijt} is the capital, L_{ijt} is the labor, and M_{ijt} represents the material inputs. The parameters α_j, β_j, and γ_j denote the intensity of use of production factors, where constant returns to scale were assumed, implying that $\alpha_j + \beta_j + \gamma_j = 1$. M_{ijt}, representing the processing stage of the operation, is composed of energy E_{ijt} and ore inputs O_{ijt}, which entered the production function in another Cobb-Douglas nested stage,

$$M_{ijt} = \left(\frac{E_{ijt}}{\eta_j}\right)^{\eta_j}\left(\frac{\lambda_j O_{ijt}}{1-\eta_j}\right)^{1-\eta_j} \quad (5)$$

where $0 < \eta_j < 1$. Idiosyncratic factors affecting the recovery rate specific to the mine and commodity are captured in the production function of each commodity by the parameter λ_j (as an ore-augmenting technical change parameter), and a parameter characterizing processing efficiency denoted by ϵ_{ij} (in Eq. (4)). These idiosyncrasies are specific to the operation regarding the material recovered and processing efficiency. Since shocks are specific to each commodity j, they affected the relative marginal cost between primary and secondary production. Accordingly, the cost function is given by the cost of inputs plus fixed costs. Considering both primary and secondary production, the cost function is:

$$C_{ijt} = r_{ijt} K_{ijt} + w_{ijt} L_{ijt} + p_{ijt}^{m} M_{ijt} + \varphi_{ijt} \quad (6)$$

where, for a given operation i and commodity $j \in \{primary, secondary\}$ in year t, w_{ijt} is the wage paid per unit of labor, r_{ijt} is the price per unit of capital, L_{ijt} is the labor input, p_{ijt}^{m} is the price per unit of material input, that is a weighted aggregate price of the price of energy p_{ijt}^{E}, and the price of ore p_{ijt}^{O}, which measures the opportunity cost of processing an additional unit of ore reserves.

The operation was optimized by considering both primary and secondary commodities. This implies that the cost of processing the unexploited minerals in the ore to produce a secondary commodity (ore-sand) was included in the overall optimization problem of the operation. Here, the economic model enabled a useful distinction between the terms 'co-product' (where the production of a secondary commodity is essential for the operation's profitability) and 'by-product' (where overall profitability is not conditional on the production of a secondary

[6] Transport costs are often modeled in this way to avoid the complexity of explicitly incorporating a transport sector into the model (Anderson and van Wincoop, 2004). Following this approach, and without loss of generality, this paper adopts a similar approach for modelling waste management and processing costs. These are included as 'iceberg'-type costs to abstract from the detailed complexity of modelling processing circuits and tailings storage facility infrastructure. However, other components in the model explicitly capture processing efficiency and rehabilitation costs, which enter more directly into the production and cost functions respectively.

commodity). The mining site is either optimizing the production of a secondary commodity given an output from primary production (by-product) or jointly optimizing production of a primary and secondary commodity (co-product), as in this setting. When secondary production is treated as a by-product, Q_{ijt} is taken as given. Whereas, when secondary production is a co-product of primary production, the decision regarding Q_{ijt} is endogenous.

3.1.1. Extensive and intensive margins of adoption

A first result of the model is the characterization of the extensive and intensive margins of adoption of secondary production for mine waste reduction. The decision to enter or exit the production of a secondary commodity, the extensive margin of adoption, is determined by the fixed costs of production. In particular, zero-profits would imply that the total variable revenue over the mine's lifetime must cover the fixed costs to produce a secondary commodity. Therefore, the entry condition and the relative production of the secondary commodity in relation to the primary operation (the intensive margin), are given by:

$$\varphi_i \leq \sum_t \left[(1-\theta) p_{it} Q_{it} - \sum_j c_{ijt} Q_{ijt} \right], \text{and} \quad \widehat{\Phi}_{it} = \left(\frac{\widehat{\Omega}_{it}}{\widehat{c}_{it}} \right)^{\varepsilon} \tag{7}$$

where $\widehat{\Phi}_{it} \equiv \frac{Q_{ij't}}{Q_{ijt}}$, $\widehat{\Omega}_{it} \equiv \left(\frac{\delta_{j'}}{\delta_j} \right) \lambda_j^{\gamma_{j'}(1-\eta_{J'})} \epsilon_{ij'} A_{ij't}$, $\varepsilon \equiv \frac{1}{1-\rho}$, and $\widehat{c}_{it} \equiv r_{ijt}^{\alpha_j} w_{ijt}^{\beta_j} \left(\left(p_{ijt}^E \right)^{\eta_j} \left(p_{ijt}^O \right)^{1-\eta_j} \right)^{\gamma_j}$, θ is a revenue tax. Recall that $p_{it} = \tau_{it} p_t^o$, with τ_{it} representing processing, transport, and waste management costs. The higher this cost, the more primary commodity the mine would have had to produce to achieve a similar level of revenue.

3.1.2. Dynamics of the mining operation

The dynamics of the mining operation were defined by decisions on how much ore to extract and mine of each commodity and how much capital to invest in each period, where capital represents the production capacity of a mine in terms of operating and sustaining capital, including equipment that was subject to depreciation and depletion over the mine's life (Aguirregabiria and Luengo, 2016). More precisely, the dynamic problem was captured by:

$$\mathscr{V}_{it}(K_{ijt}, O_{ijt}) = \max_{\mathbf{x}_{ijt}} \left\{ \pi_{it} + \frac{1}{1+\vartheta_{t+1}} \mathbb{E}_t \left[\mathscr{V}_{it+1}(K_{ijt+1}, O_{ijt+1}) \right] \right\} \tag{8}$$

where $\mathscr{V}_{it}$ is the value function, π_{it} is the current period profit, ϑ_{t+1} is the discount factor, $\mathbb{x}_{\mathbf{ijt}} = \{L_{ijt}, E_{ijt}, O_{ijt}, I_{it}\}$ and $\mathbb{E}_t[K_{ijt+1}, O_{ijt+1}]$ denote the expected value over future capital and ore reserves. This is subject to $\pi_{it} = p_{it}\mu_i \left(\sum_j \delta_j Q_{ijt}^{\rho} \right)^{1/\rho} - \sum_j c_{ijt} Q_{ijt} - \varphi_i$, the previous production and costs functions, and the following conditions of capital depreciation: $K_{ijt+1} = I_{ijt} + (1-\zeta) K_{ijt}$, capital adjustment costs $\frac{h}{2}\left(K_{ijt+2} - K_{ijt+1} \right)^2$ (González, 2022), and ore-reserves, given by:

$$O_{ijt+1} = O_{ijt} - \left(\frac{Q_{ijt}}{g_{ij}} \right) \tag{9}$$

where g_{ij} represents the ore-grades (Aguirregabiria and Luengo, 2016).

3.1.3. Output price volatility

Following a well-established body of literature (see e.g. Schwartz, 1997; Cortazar and Casassus, 1998; Andersson, 2007; Bernard et al., 2008; Evatt et al., 2012; Redlinger and Eggert, 2016), it was assumed that output price evolution follows a mean-reverting process, implying that prices of commodities tend to return to their long-term average. In continuous time, this behavior is characterized by the following stochastic differential equation representing a geometric mean-reverting process:

$$dp_{jt} = \kappa_j \left(\varrho_j - p_{jt} \right) dt + \sigma_j^p p_{jt} d\omega_t \tag{10}$$

where p_{jt} is the price at time t, κ_j is the rate at which prices reverted to the average, ϱ_j is the long-term average price, σ_j^p is a measure of price fluctuations, and $d\omega_t$ represents stochastic changes over time following a Wiener process (Brownian motion). This modelling assumption, consistent with observed behavior of mineral commodity prices, captured how prices naturally moved back toward a long-term average. The expected future price at a given time $u > t$, $p_{j,u}$, conditional on the current price p_{jt} at time t, is $E\left[p_{j,u} \middle| p_{jt} \right] = \varrho_j + \left(p_{jt} - \varrho_j \right) e^{-\kappa_j(u-t)}$. Hence, the future output price gradually approaches the long-term average output price ϱ_j, with the speed of this adjustment determined by κ_j.

3.2. Model calibration and simulation

To derive quantitative predictions from the model, the case of a representative medium-to large-scale iron ore mine, the Brucutu Mine, was simulated. Parameters related to primary production were chosen to best represent the scale of this operation. For this purpose, secondary data for the years between 1994 and 2013 from S&P Global Market Intelligence (Mine Economics SNL Metals and Mining) were used to define the business-as-usual scenario. Parameters for secondary production were selected to reflect the information provided in technical reports on the production of ore-sand following the work of Golev et al. (2022), and insights from Vale's ore-sand production company, Agera. A full list of parameters used for the simulation analysis is provided in Table 1, while a description of the initial values for simulations is presented in Table 2.

The model calibration and simulation are summarized as follows. First, the set-up was defined by the production technology, cost structure, and initial values of the mining operation, while also accounting for stochastic factors and the optimal factor demands in each period. Second, Monte Carlo simulations were run to simulate profits in each period based on commodity prices, production growth rates, taxes, and tailings management and mine closure and rehabilitation costs. Exogenous state variables included prices and ore grades, while the endogenous state variables consisted of capital investment and ore reserves. Control variables included labor and energy inputs. The Monte Carlo simulations serve primarily to evaluate the profitability of the different adoption scenarios, while properly accounting for price volatility within the dynamic optimization problem.

The general structure of the model was defined to resemble the case of the Brucutu mine, assuming a mine life of 30 years, with a discount rate of 0.05. A corporate tax rate of 35% was also assumed. Initial production of iron ore was set at 3 million tons, while the production of the secondary commodity was set to 40% of the scale of iron ore production in equivalent units. An annual production growth rate of 3% was assumed, with both primary and secondary production following the same growth rate over the life of the mine.

Note that the model does not capture endogenous production expansion but instead takes the production trajectory as given, to focus on input allocation and profitability. The production path is specified as: $Q_{ij,t} = Q_{ij,t-1}\left(1 + g\left(1 - \frac{1}{2}h_i(t - t_p)\right)\right)$, where $g = 0.03$ is the growth rate, h_i is the decline rate, set to 0.5 for primary production, and 0.65 for secondary production, indicating a faster decline for secondary output as the mine approaches the end of its life. t_p denotes the peak production year, defined as year 20 for primary production and year 25 for secondary production. To reflect the lagging volumes of secondary production as the life of the mine advances. Sensitivity analyses were conducted on growth rates, discount factors, and other key parameters to assess the robustness of the results.

Once the initial production values were defined and input elasticity

Table 1
Parameters of the production and cost structures.

Description		Value		Source
		Primary	Secondary	
σ	Elasticity of substitution	0.33		Agera Operation
ζ	Depreciation rate of capital	0.10		Gross and Hansen (2013)
θ	Tax rate to revenue	0.35		S&P
r	Discount rate	0.05		Armstrong et al. (2019)
$\%\Delta Q_{ijt}$	Growth rate of production	0.03		S&P
t	Mine life in years	30		Armstrong et al. (2019)
δ_j	Relative intensity of production	0.95	0.05	Agera Operation
α_j	Elasticity of capital	0.30	0.30*	S&P
β_j	Elasticity of labor	0.40	0.40*	S&P
γ_j	Elasticity of material inputs	0.30	0.30*	S&P
η_j	Intensity of use of energy inputs	0.80	0.80*	S&P
τ_i	Iceberg costs (per unit of production):			
Transport costs		0.30	0.015**	S&P
Processing costs		0.15	0.008**	S&P
Waste management costs		0.10	−0.05***	Agera Operation
Price volatility of each commodity (USD per dry metric ton)				
Initial price of the commodity		100	8.0	Golev et al. (2022)
Average price of the commodity		120	10.0	Golev et al. (2022)
Price volatility of the commodity		0.05	0.05	Armstrong et al. (2019)
Mean reversion speed of the price of the commodity		0.65	0.65	Armstrong et al. (2019)

Notes: The production growth rate is assumed to represent the average annual growth rated of the Brucutu operation reported in the S&P data. Transport costs, waste management costs, and additional costs associated with processing enter with an iceberg structure discounting revenues per unit of production, captured by the parameter τ_{it}. Transport costs are computed from S&P data, including port loading and inland transport costs. Transport costs associated with ore-sand production are lower, as they are assumed to serve only the domestic market. Additional costs associated with processing (e.g., reagent costs) are also calculated from S&P data. *Assumed to be the same as the primary operation. **Assumes a 5% cost share of primary production. ***Waste management costs of the primary operation are discounted by the waste reduction factor associated to ore-sand specifying the different scenarios of waste reduction.

Table 2
Initial values and cost variables.

Variable		Value		Source
		Primary	Secondary	
Initial values of production:				
Q_{ijt}	Production	3.0e06	1.2e06*	S&P
Initial values of inputs:				
K_{ijt}	Units of capital	479e06	24e06**	S&P
L_{ijt}	Labor (hours per year)	6.7e06	0.33e06**	S&P
M_{ijt}	Material inputs:			
O_{ijt}	Ore inputs (metric tons)	60.0e06	3e06**	S&P
E_{ijt}	Energy (kWh)	153.1e06	7.7e06**	S&P
Input prices (target moments):				
r_{ijt}	Cost of capital (USD per unit of capital)	0.1		Cox et al. (2022)
w_{ijt}	Cost of labor (wage per hour)	12.72		S&P/Brucutu Operation
p^m_{ijt}	Cost of material inputs:			
p^O_{ijt}	Ore inputs (USD per unit of tonne)	0.62		S&P
p^E_{ijt}	Energy (USD per kWh)	0.14		S&P/Brucutu Operation
ϕ_j	Fixed costs (USD)	2e09	0.1e09	S&P/Agera Operation
ϕ_j	Rehabilitation costs (USD)	2e09	-	Assumed

Notes: Initial values and cost variables for secondary production (ore-sand) are based on technical advice, previous research (Golev et al., 2022), and to match the ore-sand production structure of Agera operation. *Assumes 40% of the primary operation as the initial value. **Assumes a 5% cost share relative to primary production.

parameters calibrated, the quantity of inputs in each period was determined by the first-order conditions of the static problem, considering growth rate and given input prices. The Euler equations determined the amounts of capital and ore-reserves in each period. Prices, production, ore reserves, and ore grades were all expressed in equivalent units of the primary commodity (Aguirregabiria and Luengo, 2016).

The substitution parameter used for the CES aggregator was specified as −2, implying an elasticity of substitution of 0.33, consistent with an assumption of low substitutability between primary and secondary production. This assumption allows for an implicit representation whereby increases in secondary production are associated with increases in primary production, a key factor motivating ore-sand adoption. The chosen elasticity of substitution reflects not only a general assumption of low substitutability between primary and secondary outputs but also match the technical characteristics of the case study. In particular, the fact that ore-sand production is constrained by the primary output (and vice versa), implying that secondary output can only expand proportionally with primary output, which justifies the low substitutability assumption. The distribution of output shares is governed by a share parameter of 0.95 for primary production, with the residual 0.05 allocated to secondary production. The details and source of these parameters are described in Table 1. While initial values used in the simulations are defined in Table 2.

For the primary commodity, initial values of capital input requirements K_{ijt} are computed to match capital costs ($r_{ijt}K_{ijt}$) reported from S&P data as the sum of operating and sustaining capital expenditures. Labor requirements L_{ijt} measured in hours per year were computed assuming 44 h per week per worker with a total number of 2651 workers per year to match the labor costs ($w_{ijt}L_{ijt}$) at S&P data of 40% of operating costs (includes total mine site costs, pelletizing costs, and indirect and extraordinary costs), assuming an average wage per hour of w_{ijt} =12.72 USD. The number of total workers is similar to the values of approximately 2500 reported at early stages of the Brucutu mine operation (Vale, 2023).[7] Ore input requirements O_{ijt} measured in metric tons are taken from S&P data average annual quantity of ore processed. The ore input price is computed to match the total average annual costs of ore extraction and processing ($p^O_{ijt}O_{ijt}$) from S&P data, which is 5% of operating costs. Energy costs ($p^E_{ijt}E_{ijt}$) are computed following 25% of operating costs according to S&P data. The total requirement of energy E_{ijt} measured in kWh is computed to match the energy costs from S&P data, assuming a price of energy of 0.14 USD per kWh.

For transport costs, the parameter $\tau_{transport}$ was set at 0.3 for the primary commodity, meaning that 30% of the revenue per unit of each commodity is allocated to covering transport costs. Additionally, a component of processing $\tau_{processing}$ and waste management costs τ_{waste} followed the same iceberg structure. Processing costs of the primary commodity were assigned as a parameter of 0.15, whereas waste management costs were set at 0.1. Regarding fixed costs, an initial cost of US $ 2b was assumed for the primary commodity. For secondary production, these costs were set to represent the relative scale of the secondary operation, implying 5% of primary production. Mine closure and rehabilitation costs totaling US$ 2b, representing a conservative assumption

[7] Vale (2022). Brucutu: the world's biggest iron ore mine. Newsroom - Mining - Vale.

(2022), were annualized over the life of mine and were only associated with the production of the primary commodity. In the adoption scenario, presented in Fig. 3, ore-sand production is assumed to reduce both waste management costs (τ_{waste}) and rehabilitation costs ($\phi_{rehabilitation}$) by 50%. Sensitivity analysis is conducted on this waste reduction factor, covering the whole range of potential values for reference.

Initial values and parameters defining price volatility are dependent on the commodity. Following Armstrong et al. (2019a,b), the initial price for the primary commodity was p_{jt} = US$ 100 per dry metric ton, with an average price ϱ_j = US$ 120, price volatility $\sigma_j = 0.05$ and mean reversion $\kappa_j = 0.65$. For the secondary commodity, these parameters and initial values were based on data from Golev et al. (2022), with an assumed average price of US$ 10 per dry metric ton, and initial price of US$ 8 with $\sigma_j = 2$, and $\kappa_j = 0.65$. Where we use the Euler-Maruyama discretization to simulate the mean reverting process described in Eqn. (10). The discretized form is $p_{jt} = p_{j,t-1} + \kappa_j\left(\varrho_j - p_{j,t-1}\right)\Delta t + \sigma_j^p p_{j,t-1}\Delta\omega_t$ with $\Delta t = 1$, representing annual variation.

4. Results and discussion

The results were structured around two main points. First, the differences in profitability by comparing the business-as-usual case with various adoption scenarios are presented.[8] Subsequently, it is shown how profitability of the most conservative adoption scenario responded to potential shocks in revenue and costs. The responses of profits to changes in output prices, recovery rates, processing efficiency, and waste-related costs were the specific focus.

4.1. Private economic benefits of mine waste reduction

The cost structure and production over the mine's life is shown in Fig. 2, in which the business-as-usual scenario is compared to the most conservative adoption scenario. The annual average total costs with adoption amounted to 36.06 US$ per tonne, whereas for the business-as-usual scenario, costs were 41.28 US$ per tonne (Fig. 2a). These values represent approximately 28% of the mean output price in the adoption scenario (130 US$ per tonne, including both primary and secondary production) and 34% in the business-as-usual case (120 US$ per tonne of iron-ore), resulting in operating margins of approximately 72% to 66%, respectively. The totals of iron ore and ore-sand produced during the mines' life amounted to more than 400 and 500 million dry metric tonnes, respectively (Fig. 2b). With an average annual production of iron-ore of 14.09 MMt, and 18.01 MMt for ore-sand, representing an average annual production ratio of approximately 1.3 tonnes of ore-sand per tonne of iron-ore, consistent with figures reported by Vale's ore-sand operations.

Although the addition of secondary production adds costs, these are distributed over a greater volume of output. The decomposition of costs into variable costs (capital, labor, energy, and ore inputs), which enter the production function; 'iceberg'-type costs, which are proportional to revenue (processing, waste management, and transport); and fixed costs (ϕ_i), is presented in Fig. 2a. While variable costs under adoption are higher than in the business-as-usual case, the proportional costs are lower, driving the reduction in total average costs per tonne. As expected, the adoption of ore-sand added costs for production factors such as capital, labor, energy, and ore inputs (Fig. 2a). However, significant reductions in waste management and rehabilitation costs are described. Waste management costs are $2.43 in the adoption scenario compared to $5.35 in the business-as-usual case (displayed in the upper right corner of the plot in Fig. 2a). Rehabilitation costs are captured through the fixed component.

Results of the annual and discounted profits from simulations under different adoption scenarios, are reported in Fig. 3, focusing on waste management and rehabilitation costs, as well as ore-sand commercialization. Specifically, expanding on Packey (2012), the analysis includes two commercialization scenarios, one with low and another with high waste management and rehabilitation costs, and two scenarios with and without commercialization under identical conditions. Theoretically, technical developments could one day enable near total tailings reduction, through full separation into different mineral by-products. For example, the fine residuals of ore-sand by-products could be agglomerated into coarse aggregates for construction applications. However, such advancements require further experimental development and validation (Golev et al., 2022). Currently, Vale's Brucutu operation has achieved annual tailings reduction of around 10% with the main constraining factors the degree of ore-sand substitution given the relatively fine particle size distribution of Brucutu ore-sand, the size of nearby sand markets and transport costs. For the base case presented here we model a 50% reduction, which is an achievable mid-term goal for the industry, and present both more conservative and more optimistic scenarios. In addition, we include sensitivity analyses to this assumption. For simplicity, all scenarios assume that both primary and secondary production were distributed free-on-board, with no storage.[9] While Fig. 3a presents the cases under ore-sand commercialization, Fig. 3b shows the scenarios in which ore-sand is not commercialized.

These suggest significant potential benefits from adopting ore-sand production rather than discharging it as waste in the primary production only operation. However, as described in Packey (2012) and captured in our model, the magnitude of these gains, in part, depends on the extent to which secondary production reduces waste management and rehabilitation costs. The distribution of these benefits over the mine's life is shown in Fig. 3a, with the mine having reached peak production at 20 years, while secondary production peaked five years later, reflecting a time lag in the utilization of ore resources for secondary production. As expected, benefits from adoption varied as mine life progressed through its life cycle. Notably, the evolution of annual profits under the business-as-usual scenario fell within the range of expected profitability defined by the most conservative and most optimistic adoption scenarios, given the specified set of parameters characterizing this representative iron ore operation. The sensitivity of these results to other key parameters was also explored.

The violin-plot in Fig. 3b displays the mean and distribution of NPV for the simulation results ($n = 1000$) for each scenario. These reveal that not all adoption scenarios for ore-sand are significantly more profitable compared to the business-as-usual scenario. The difference between the most conservative adoption scenario of waste management and rehabilitation costs, in which the secondary commodity was commercialized, and the business-as-usual case was about US$ −0.33b on average, however, the operation is still profitable with an average NPV of US$ 3.84 across the simulations. For the more optimistic adoption scenarios (100% of reduction in waste management and rehabilitation costs, modeled to reflect an upper-bound limit of profitability), the benefits increased to an average of US$ 0.74b compared to the business-as-usual case. This represented an additional US$ 1.07b in gains over the conservative adoption scenario. Even when ore-sand was not commercialized (essentially given away for free) the gains for adoption were of comparable magnitude in comparison to business-as-usual. This indicates that the reduction in costs associated with managing tailings storage facilities and mine closure and rehabilitation can outweigh the costs of secondary production, even after accounting for the initial investments required to establish a processing circuit for the secondary commodity, provided that the scale of production is sufficient to

[8] A detailed discussion of scenarios involving mine waste utilization through multiproduct adoption in mining operations is presented in Packey (2012).

[9] In more realistic modelling, particularly for early adopters of ore-sand, output levels may be more sensitive to final demand conditions and short-term storage costs (Golev et al., 2022).

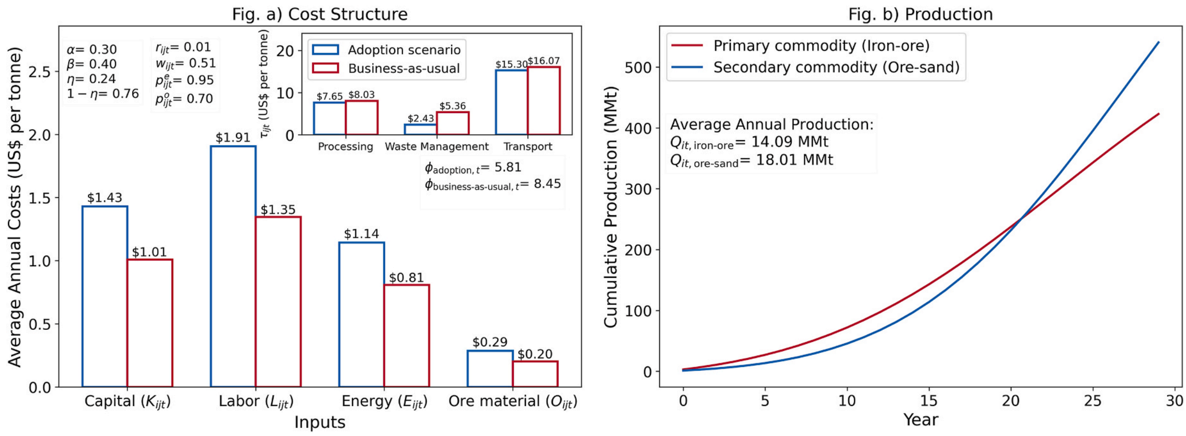

Fig. 2. Cost structure and production over the mine's life.
Notes: Figure shows the structure of average annual costs (Fig. a) and the cumulative production over the mine's life (Fig. b). The structure of costs is expressed in US$ per tonne of iron ore production, where ore-sand was included as equivalent units of iron ore. The convention to use dry metric tonne as a unit was followed, given comparability and independence from water. Regarding the cost structure, input elasticities for capital, labor, energy, and ore materials are displayed in the figure (average across primary and secondary outputs), as well as input prices. In addition, iceberg-costs are plotted, in the form of processing, waste management, and transport costs, distinguishing between the adoption and the business-as-usual scenario. The cost ratios between the business-as-usual and adoption scenarios are determined by the CES productivity shifter, the processing efficiency, the material recovery factor, and the input elasticities. This costs and production structure is obtained from the calibration of the model described in Section 3.2.

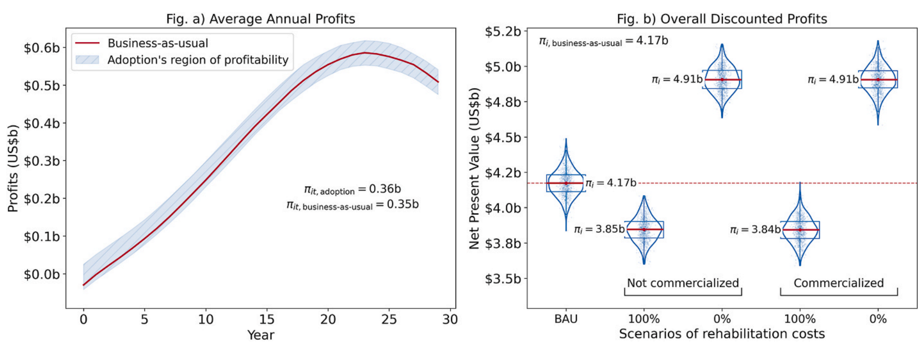

Fig. 3. Economic benefits from the adoption of secondary production for mine waste reduction.
Notes: The figure shows the yearly profits computed from the simulations (n = 1000 for each scenario) over a 30-year life-of-mine (Fig. a) and the Net Present Value (NPV) for the different scenarios (Fig. b). Fig. a describes the evolution of the yearly profits under the business-as-usual and the expected region of profitability of ore-sand adoption, assuming commercialization at an average of US$ 10 per tonne. The relative profitability of adoption compared to business-as-usual is non-monotonic over time. The lower bound of the adoption region corresponds to simulations over the most extreme scenario with no reduction in waste management and rehabilitation cost, while the upper bound reflects the most optimistic case of 100% waste management and rehabilitation cost reduction. The figure also displays the average yearly profits of adoption (US$ 0.36b) and business-as-usual (US$ 0.35b). Fig. b shows the NPVs associated with each scenario including a case where ore-sand is not commercialized but instead given away at no revenue. BAU is the business-as-usual case, extreme scenarios are included as a reference, 100% represents the full investment in ore-sand infrastructure without any reduction in waste management and rehabilitation costs, while in the 0% scenarios, all waste management and rehabilitation costs are reduced. These scenarios were modeled as a reference of upper and lower bounds of the potential profitability of adoption. A reduction of at least 40% in waste management and rehabilitation cost is sufficient to achieve profitability levels equivalent to the business-as-usual scenario.

generate substantial savings in waste-related costs.[10]

4.2. Adoption amid cost and revenue productivity shocks

To further explore the profitability of adoption under different parameter combinations, Fig. 4 presents how the NPV varies with changes in key cost factors.[11] Fig. 4a illustrates the combination of variable and fixed waste-related costs from the primary operation, while Fig. 4b shows the discounted profits under varying combinations of processing and transport costs for ore-sand. In both panels, the black contour line represents the average NPV level of the business-as-usual scenario, based on the simulations across the specified parameter values. The red color gradient indicates cost combinations where the average NPV of ore-sand adoption falls below that of business-as-usual, while the blue gradient highlights combinations where adoption yields a higher average NPV across simulations.

Fig. 4a, illustrates the extent to which waste-related costs associated with the primary commodity need to be reduced through ore-sand production for adoption to become more profitable than business-as-usual. The results indicate that, in a case where ore-sand does not reduced the fixed waste-related costs associated with rehabilitation (i.e., assuming rehabilitation costs of US$ 2b., represented by the 100% fixed component in the figure), variable waste-related costs would need to be reduced by approximately 8% of total revenue (corresponding to an 80% reduction from the baseline parameter) for adoption to surpass business-as-usual in profitability, assuming all other aspects of the production and

[10] It is worth repeating that an additional benefit not accounted for here is any improvement in primary commodity production that may result from reducing tailings and their influence on production.

[11] Golev et al. (2022) provide a comprehensive technical description of the critical factors influencing ore-sand adoption.

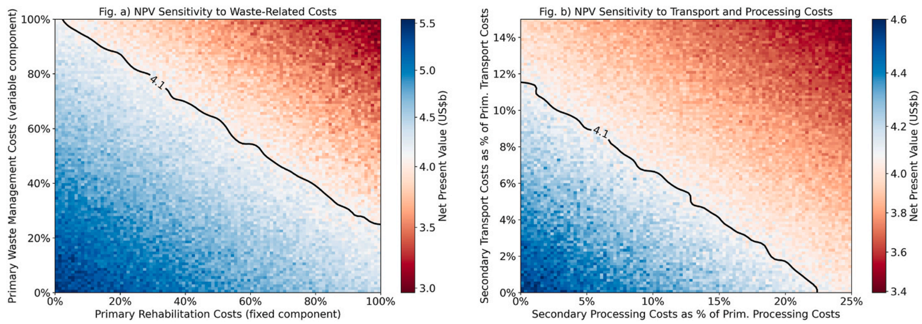

Fig. 4. Profitability, waste management and rehabilitation, transport, and processing costs.
Notes: The figure illustrates the effect on the NPV of changes in key cost parameters in the model. Fig. a shows the impact of the variable and fixed components associated to waste management and rehabilitation. Fig. b presents the effects of processing and transport cost for ore-sand, expressed as a share of the corresponding costs for the primary operation. The black contour line shows the average NPV for the business-as-usual case over the potential range of values. The blue dots represent point at which the adoption scenario is more profitable than business-as-usual, while the red dots indicate points at which the adoption scenario yields lower profits than business-as-usual. The axis values in Fig. b, are restricted to the relevant interval to clearly visualize the extent to which the adoption scenario is more or less profitable than business-as-usual. Waste management, transport, and processing costs enter the model through an 'iceberg'-type cost structure. Rehabilitation costs are modeled as a fixed cost for simplicity with values chosen to reflect the overall scale of the operation. More precisely, these costs are assumed to be known at the beginning of the mine's life, based on the total resources expected to be depleted. They are then annualized and incorporated as a fixed cost in each year of the operation. Consequently, the adoption of secondary production would reduce the volume of mine waste, thereby lowering both variable waste management costs and fixed rehabilitation costs. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

cost structure of this representative iron ore mine remain constant.[12]

At the other extreme, in a scenario without rehabilitation costs, assuming these are fully absorbed by ore-sand production, adoption becomes more profitable than business-as-usual even if variable waste-related costs remain as high as 10% of the operation's total revenue. More generally, any scenario in which both fixed and variable waste-related costs are reduced by approximately 50% of their baseline levels results in higher profitability compared to business-as-usual. For cost reductions below that threshold, a smaller reduction in one component would need to be offset by a greater reduction in the other.[13]

Nonetheless, Fig. 4a also suggests that while the degree of waste-related cost reductions affects the relative profitability of adoption, it does not necessarily lead to absolute losses for the overall operation under the structural assumptions of this representative iron ore mine.

Fig. 4b shows that both processing costs and transport costs of ore-sand should be sufficiently low for adoption to outperform the business-as-usual scenario. Specifically, on average adoption becomes more profitable than business-as-usual when processing and transport costs are reduced by approximately 20% and 10%, respectively, relative to the baseline costs for the primary commodity. This is equivalent to about 3% of total revenue for each of these components, implying that adoption is more likely to be more profitable than business-as-usual when transport and processing costs from the secondary operation remain below 3% of the total revenue, *ceteris paribus*. Like the case of waste-related costs, Fig. 4b also captures some degree of substitutability between processing and transport costs at low levels, suggesting that higher costs in one component can, to some extent, be offset by lower costs in the other. This supports the view that ore-sand markets closer to mine sites should be prioritized, while processing should partially rely on existing infrastructure necessary for the primary operation (Golev et al., 2022). Both processing and transport cost exert a substantial influence on the profitability of the operation and can significantly reduce its value if they are excessively high relative to those of the primary commodity.

Given the high uncertainty related to the technical aspects of ore-sand. Two additional exercises were conducted to examine uncertainty in the adoption of secondary production. Fig. 5 explores how differences in production technologies, related to material recovery and efficiency in the processing circuits, in the adoption of the secondary commodity might affect overall profitability (Fig. 5a), as well as the potential impact of demand shocks captured through variations in output prices (Fig. 5b).

The two key parameters capturing technological differences in production are the material recovery factor λ_{ij} and the processing efficiency ϵ_{ij}. The parameter λ_{ij}, reflects exogenous factors affecting material recovery, with lower values associated with reduced profitability. Processing efficiency ϵ_{ij}, on the other hand, indicates how effectively ore inputs are transformed into outputs. By varying these parameters, it is possible to observe how the overall value of the operation responds to shifts in production efficiency. The results show that differences in NPV could be substantial when both λ_j and ϵ_j values fall below 0.5, reflecting low recovery rates and processing efficiency. However, even within this range, the effects are smaller in magnitude compared to the variations in NPV driven by changes in waste management and rehabilitation costs.

Material recovery and processing efficiency represent a complementary relationship, indicating that both factors would have to exceed moderate levels for ore-sand adoption to yield higher returns relative to the business-as-usual scenario. Factors such as particle size distribution of ore inputs, and the coarseness requirements for ore-sand applications may impact processing efficiency both positively and negatively, while the recovery rates of the primary output can influence the material recovery factor for ore-sand. For example, coarse particle flotation has been adopted (irrespective of ore-sand) to increase processing efficiency, as the cost savings from reductions in griding and energy outweigh the losses in resource recovery.

Reflecting typical mining operations, very low levels of either factor led to sharp declines in overall NPV. Conversely, the gradient flattened at higher values of recovery and efficiency, above approximately 70%, indicating diminishing returns to further technological improvements in this range.

[12] Note that there are scenarios in which production of the secondary ore-sand by-product could temporarily be halted due to excessively high input costs or low output prices. However, such shutdown decisions are not modeled as an option during the life of the mine in our framework. The purpose of this model is broader, to assess how these factors influence overall profitability over time. As a result, the simulation results may underestimate the potential profits from ore-sand adoption, particularly in scenarios where operation flexibility could mitigate losses or enhance profitability.

[13] This reasoning assumes a case where no other changes to production result from the introduction of ore-sand, such as improved efficiency of the primary commodity that results from reducing tailings and any constraints on production.

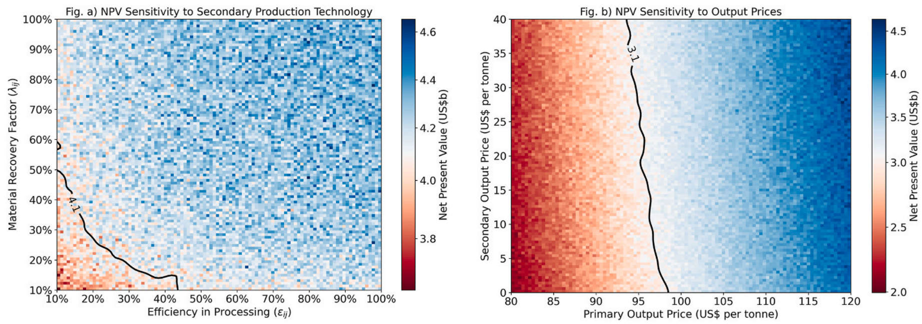

Fig. 5. Profitability, secondary production technology, and output prices.
Notes: The figure demonstrates the effect on the NPV for different values of key parameters in the model, capturing exogenous variation in factors associated with the recovery and processing of minerals and materials (Fig. a), as well as market conditions captured by output prices (Fig. b). The relevant interval of prices illustrated in Fig. b, is based on Golev et al. (2022), Armstrong et al. (2019a,b), and operational feedback from Vale's ore-sand operation. The black contour line depicts the average NPV for the business-as-usual scenario across the full range of parameter values. Blue points indicate cases where adoption outperforms business-as-usual, whereas red points correspond to cases were adoption results in lower profitability. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Fig. 5b shows that variation in the price of the secondary output had negligible impacts on overall NPV, and the adoption profitability in relation to business-as-usual was mostly driven by the price of the primary commodity. Given the low substitutability between primary and secondary outputs ($\rho = -2$), and the significantly larger importance of primary relative to secondary production in revenue ($\delta_{primary} = 0.95$), changes in the primary output price largely determined whether the adoption scenario yielded greater benefits than business-as-usual.

Simulation results suggest a threshold of approximately US$ 100 per tonne of iron ore. Above this level, the adoption scenario yielded lower absolute profits than the business-as-usual case, on average. This result is also consistent with the observation that the profitability of adoption is relatively insensitive to price changes. Aggregates markets are typically characterized by both low prices and low volatility (Da and Le Billon, 2022; Golev et al., 2022), especially when compared to metal commodities. As a result, revenue from secondary production is less affected by price uncertainty, not only due to the limited price variation but also because it contributes a smaller share of total revenue (additional results describing relative price volatility are presented in the Appendix). Consequently, the price of secondary output plays a less significant role in determining the relative profitability of adoption.

Finally, the operation exhibits substantial variation in NPV across different combinations of high-level parameters, specifically, the annual growth rate of production (for both primary and secondary outputs), the discount rate, and varying levels of waste management and rehabilitation costs (see Appendix Table B.4.). The strong compounding effect of production growth translates into substantial profitability gains, especially at lower discount rates. This is a critical consideration for ore-sand adoption, particularly since primary production can be constrained by the volume of waste material generated, as observed in the case study. In this context, waste reduction enabled by ore-sand adoption could not only lower waste management and rehabilitation costs but also alleviate physical constraints imposed by tailings storage facilities, thereby unlocking additional primary production. This, in turn, could lead to higher output and faster growth rates. This effect is implicitly captured in the model through technological complementarities in the production function, as reflected by the low elasticity of substitution between primary and secondary outputs $\sigma = 0.33$. The significant variation in NPV across different growth scenarios, underscores the potentially large gains that could result from expanding production capacity through waste reduction.

4.3. Discussion

Recent disasters caused by the failure of tailings storage facilities have generated significant concerns about waste management practices in the industry (Bowker and Chambers, 2015). Both industry and governments have begun to explore potential solutions to address this issue (ICMM, 2020). In this context, the economic incentives for mining companies to reduce tailings by adopting large-volume ore-sand secondary products were studied.

In general, the analysis demonstrated that the impact of fundamental uncertainties related to the adoption of ore-sand played a significantly smaller role than the substantial influence of reducing waste management and rehabilitation costs on overall profitability. These results highlighted the economic benefits of adopting ore-sand as a secondary product, particularly for mitigating the costs associated with mine waste, including tailings, mine closure and rehabilitation costs. This suggests that, even under varying levels of uncertainty in the mine, the adoption of ore-sand could be a viable strategy for the long-term profitability of a mining operation. Notably, a key advantage of ore-sand compared to other options of secondary production is its high effectiveness in reducing the volume of mine waste of an operation, which could translate into lower waste management and rehabilitation costs.

Importantly, tailings storage facilities can become increasingly costly as mine waste volumes grow, particularly for large and long-lived operations. These costs accumulate over the life of the mine and typically include substantial capital expenditures (Labonne, 2016; Armstrong et al., 2019a,b). Our model simplifies these complexities by representing waste-related costs through a variable (iceberg type) and a fixed cost component, without explicitly capturing the discrete dynamics of the large investments associated with tailings storage facility infrastructure over the life of the mine. If these costs are substantial, as suggested by Armstrong et al. (2019a,b), then the economic incentive for waste reduction through ore-sand adoption would, in fact, be even stronger than our model predicts, especially when tailings failure risks are considered. Our quantitative results should therefore be interpreted as conservative, lower-bound estimates of the potential private economic gains from adoption.

To put the scale of these risks in perspective, claims for fines and reparations following a single tailings dam failure, such as the Samarco Mariana dam failure in Brazil, have range from around US$5b to as high as US$ 55b (Armstrong et al., 2019a,b). These amounts are comparable to, or well in excess of, the net present value of the entire operation modeled here. Against potential losses of this magnitude, even a small reduction in failure risk yields large expected savings, particularly as such failures have become more frequent over time (Armstrong et al., 2019). A quantitative framework for such valuations is provided by Armstrong et al. (2019a,b), who incorporate the probability and cost of tailings dam failure directly into the valuation of an iron ore project. They find that a treatment process that reduces the volume of unconsolidated tailings raises the project value by roughly 20% relative to business-as-usual once failure risk is accounted for, while reinforced dam maintenance adds about 8%. Because ore-sand likewise reduces the volume of tailings, and hence the risk of failure, a benefit of comparable order would plausible be associated with adoption. Since this channel is not captured in our model, these potential savings reinforce the interpretation of our estimates as conservative lower bounds.

The industry is increasingly moving towards adopting similar production technologies and better mine waste reduction and management practices, as demonstrated by Vale in Brazil (Vale, 2022, 2023) and by the introduction of the Global Industry Standard on Tailings Management (ICMM, 2020, 2024). Mining companies are further incentivized to adopt these practices when production is capped by the volume of waste material generated and held in storage facilities, meaning that reducing mine waste could allow for increased production. Even though secondary products' profitability depends on access to final markets, the adoption scenarios are still profitable compared to business-as-usual. Moreover, in some instances, the mining companies themselves may serve as the market, such as when ore-sand is used for development and maintaining mining infrastructure, such as road base for haul roads, or as the fine aggregate in shotcrete used for tunnel construction (Segura-Salazar et al., 2026).

Importantly, ore-sand co-production illustrates the circular economy in the mining context. Rather than recycling material that has already been discarded, it recovers, within the mineral processing circuit, silicate minerals that would otherwise become tailings, keeping them in productive use as a construction material and thereby reducing the very waste stream that determines a mine's long-term footprint and liabilities. Our framework contributes a quantitative economic assessment of such a strategy, making explicit the cost and revenue channels through which it becomes privately profitable. This circularity operates along two complementary pathways. Within the mine, it prevents waste at source, diverting material from a waste stream into a product, reducing the volume, cost, and risk of waste that would otherwise require long-term management. Beyond the mine, it links the mining and construction sectors, by substituting for natural sand sourced from rivers and coasts, relieving the environmental pressures associated with sand extraction, one of the largest flows of raw material in the global economy (UNEP, 2022). Our results show that the primary economic incentive arises from avoided tailings constraints, waste management, rehabilitation and closure costs, not from ore-sand revenues. This distinguishes ore-sand from higher-value, lower-volume circular strategies such as the recovery of critical minerals from tailings (Abbadi and Mucsi, 2024), positioning the two as complementary components of a much broader circular economy transition in the mining sector (Lèbre et al., 2017b; Franks, 2020; de Palacios and Espí, 2022).

5. Conclusions

This paper has quantified the private economic incentives for adopting ore-sand as a large-volume secondary product in a representative iron ore operation. Using a dynamic optimization model calibrated to Vale's Brucutu mine and informed by operational data from its ore-sand operation, we showed that ore-sand co-production can generate substantial additional profits relative to a business-as-usual scenario, mediated by reductions in the costs of tailings management, tailings storage, and mine rehabilitation. These incentives shape the extensive margin (the decision to adopt ore-sand technology) and the intensive margin (the scale of co-production once adopted), and remain robust in the face of uncertainty in commodity prices, ore grades, recovery rates, and processing costs.

The analysis highlights that ore-sand occupies a distinct niche in the broader landscape of production innovations for mine waste reduction. The literature tends to focus on the recovery of critical minerals and high-value metals from tailings, which are typically characterized by high unit values but low production volumes and often substantial additional processing costs and technical risk. By contrast, ore-sand is a low-price, high-volume product whose primary economic contribution is to reduce the cost and risk associated with mine waste streams. Its profitability is driven less by the revenue from selling sand-like products, and more by cost savings and by relaxing physical constraints on tailings storage that can otherwise limit primary production. In this sense, critical mineral recovery and ore-sand co-production can be viewed as complementary rather than competing strategies: the former targets the value locked in a small fraction of the waste stream, while the latter addresses the bulk of the material that ultimately determines mine footprints, tailings storage risk profiles, and long-term liabilities.

Our findings also point to specific levers through which policy can accelerate the adoption of ore-sand and similar co-production technologies by de-risking the required upfront investment. First, green mining bonds and sustainability-linked financing instruments could explicitly recognize investments that reduce tailings volumes and tailing storage failure risk through lower borrowing costs. Second, targeted tax incentives for waste reduction (for example, accelerated depreciation or investment tax credits for tailings-reducing technologies) could tip marginal projects from being privately unprofitable to investment-ready. Third, streamlined and better-coordinated permitting processes for mines that adopt co-production technologies consistent with best-practice tailings governance, such as the Global Industry Standard on Tailings Management (ICMM, 2020), could reduce regulatory uncertainty and shorten payback periods. Together, such policies would align private incentives with emerging societal expectations that tailings risks be systematically reduced.

While the model developed here focuses on private net present value, the potential social benefits of mine waste reduction are considerably broader. Reducing tailings volumes lowers the probability and severity of tailing storage failures, mitigates chronic environmental and social harms from long-term waste storage, and can displace environmentally damaging sources of construction aggregates, such as river sand mining or additional rock crushing. Future work could embed ore-sand co-production within a more comprehensive social cost–benefit framework that explicitly monetizes these externalities. One promising approach would be to incorporate a shadow price on the carbon emissions avoided when ore-sand substitutes for natural sand or crushed rock, alongside a risk-adjusted expected cost of potential tailings storage failures. These terms could be added directly to the NPV calculation as additional benefit components or avoided-cost streams, yielding a social NPV that can be compared with the purely private NPV estimated in this paper.

By quantifying the private economic case for ore-sand, this paper helps to clarify a key element needed to assess its broader social benefits. As mining companies and regulators confront rising waste volumes alongside tightening social and environmental expectations, co-production strategies such as ore-sand offer a scalable pathway to reduce tailings failure risks, support primary production, and enhance the sustainability of construction-material supply chains. Although the model was calibrated to the specific context of Vale's Brucutu operation, its underlying structure was intentionally designed to be generalizable to other commodities, mine operations, and geological settings. The framework remains parsimonious yet sufficiently flexible to capture the heterogeneous complexity of the mining sector. Future applications would primarily require calibrating the model to the specific contexts rather than modifying the fundamental equations of the model. This reinforces our contribution as presenting a foundational tool for future research on mine waste reduction, mine waste valorization, and options for secondary production.

Extending the model to other commodities requires distinguishing the model's structure, which is invariant across contexts, from its calibration, which is context specific. Although the underlying equations of the model remain unchanged (i.e., the structural elements such as production technology and cost structure), applying the model to copper, gold, or rare earths would primarily require calibrating four sets of parameters: (1) the primary output price and its mean reversion and volatility parameters, which differ substantially across commodities; (2)

ore grades and the secondary-to-primary production ratio, since the lower grades typical of gold and many critical minerals generate proportionally more waste, and therefore a larger potential ore-sand stream; (3) the recovery factor and processing efficiency of the secondary product, which depend on the mineralogy and particle size distribution; and (4) the input cost shares, discount rate, royalty and taxes, and waste-related cost reductions, which are specific to each operation.

At the same time, the model abstracts from specific details such as mine design and planning over its lifecycle, to maintain a simple and tractable structure that aligns with data from mining operations. Other aspects, such as temporary closures, cutoff grade optimization, final market demand, and environmental externalities, are also left for future research. Material inputs could be further decomposed into energy and non-energy inputs, as significant energy use is associated with different mineral processing and recovery rates. Savings in water consumption from the adoption of secondary production could also be incorporated. Since waste processing involves moving particles with water, reducing the waste material directly translates into lower freshwater usage (e.g., due to increased water recovery for processing). This potential reduction in water consumption is a major economic incentive for mining companies in places with low tailings failure risks and water scarcity, such as Australia and Chile. Moreover, the model capture waste-related costs through a simplified, albeit novel, cost structure. Therefore, substantial costs associated with tailings storage facilities are not explicitly incorporated in our model. These include the discrete investments required for the expansion of these facilities over the life of the mine, as well as the risks of tailings dam failure, both of which can be substantially reduced through ore-sand adoption. Because of these simplifications, our quantification of the private economic gains from ore-sand adoption should be consider lower-bound estimates of the potential economic gains.

Finally, a promising avenue for future research lies in explicitly modelling the feedback mechanisms through which secondary production reduces physical constraints on the primary operation. This channel of profitability is particularly relevant in contexts were tailings storage capacity limit primary production. By lowering the volume of mine waste, ore-sand adoption can unlock additional primary output and raise long-term growth. While this effect is implicitly captured in the current model through the low substitutability assumption between primary and secondary production technologies, quantifying its magnitude would require more explicit modelling on the endogenous relationship between primary production and mine waste. A better understanding of these mechanisms could further strengthen the economic case for adopting ore-sand and similar waste-reduction technologies in the mining sector.

CRediT authorship contribution statement

Juan Soto-Diaz: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing. **Steven Micklethwaite:** Conceptualization, Funding acquisition, Investigation, Project administration, Supervision, Writing – review & editing. **Ian A. MacKenzie:** Conceptualization, Funding acquisition, Investigation, Supervision, Writing – review & editing. **Juliana Segura-Salazar:** Conceptualization, Investigation, Writing – review & editing. **Flavio Menezes:** Conceptualization, Investigation, Writing – review & editing. **Eva Marquis:** Investigation, Writing – review & editing. **Karen Hudson-Edwards:** Funding acquisition, Investigation, Writing – review & editing. **Daniel M. Franks:** Conceptualization, Funding acquisition, Investigation, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Daniel Franks reports financial support was provided by Australian Research Council. Karen Hudson-Edwards reports financial support was provided by UK Research and Innovation. Eva Marquis reports financial support was provided by UK Research and Innovation. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Model summary equations

A.1 Production

$$Q_{it} = \mu_i \left(\sum_j \delta_j Q_{ijt}^{\rho} \right)^{1/\rho} \tag{A.1.1}$$

$$Q_{ijt} = \nu_j \epsilon_{ij} A_{ijt} K_{ijt}^{\alpha_j} L_{ijt}^{\beta_j} \left(\lambda_j M_{ijt} \right)^{\gamma_j} \tag{A.1.2}$$

$$M_{ijt} = \left(\frac{E_{ijt}}{\eta_j} \right)^{\eta_j} \left(\frac{\lambda_j O_{ijt}}{1 - \eta_j} \right)^{1-\eta_j} \tag{A.1.3}$$

A.2 Cost

$$C_{ijt} = r_{ijt}K_{ijt} + w_{ijt}L_{ijt} + p_{ijt}^{m}M_{ijt} \tag{A.2.1}$$

$$p_{ijt}^{m}M_{ijt} = p_{ijt}^{E}E_{ijt} + p_{ijt}^{O}O_{ijt} \tag{A.2.2}$$

$$C_{it} = \varphi_{it} + \sum_{j} c_{ijt}Q_{ijt} \tag{A.2.3}$$

A.3 Marginal products

$$r_{ijt} = \mu_{ijt}\nu_j\epsilon_{ij}\alpha_j A_{ijt}K_{ijt}^{\alpha_j-1}L_{ijt}^{\beta_j}\left(\lambda_j\left(\frac{E_{ijt}}{\eta_j}\right)^{\eta_j}\left(\frac{\lambda_j O_{ijt}}{1-\eta_j}\right)^{1-\eta_j}\right)^{\gamma_j} \tag{A.3.1}$$

$$w_{ijt} = \mu_{ijt}\nu_j\epsilon_{ij}\beta_j A_{ijt}K_{ijt}^{\alpha_j}L_{ijt}^{\beta_j-1}\left(\lambda_j\left(\frac{E_{ijt}}{\eta_j}\right)^{\eta_j}\left(\frac{\lambda_j O_{ijt}}{1-\eta_j}\right)^{1-\eta_j}\right)^{\gamma_j} \tag{A.3.2}$$

$$p_{ijt}^{m} = \mu_{ijt}\nu_j\epsilon_{ij}\gamma_j A_{ijt}K_{ijt}^{\alpha_j}L_{ijt}^{\beta_j}\left(\lambda_j\left(\frac{E_{ijt}}{\eta_j}\right)^{\eta_j}\left(\frac{\lambda_j O_{ijt}}{1-\eta_j}\right)^{1-\eta_j}\right)^{\gamma_j-1} \tag{A.3.3}$$

$$p_{ijt}^{E} = \iota_{ijt}\eta_j^{1-\eta_j}E_{ijt}{}^{\eta_j-1}\left(\frac{\lambda_j O_{ijt}}{1-\eta_j}\right)^{1-\eta_j} \tag{A.3.4}$$

$$p_{ijt}^{O} = \iota_{ijt}(1-\eta_j)^{\eta_j}\left(\frac{E_{ijt}}{\eta_j}\right)^{\eta_j}O_{ijt}{}^{-\eta_j} \tag{A.3.5}$$

A.4 Conditional factor demands

$$K_{ijt} = \alpha_j\left(\frac{Q_{ijt}}{\lambda_j^{\gamma_j}\epsilon_{ij}A_{ijt}}\right)\frac{w_{ijt}^{\beta_j}\left(p_{ijt}^{m}\right)^{\gamma_j}}{r_{ijt}^{\beta_j+\gamma_j}} \tag{A.4.1}$$

$$L_{ijt} = \beta_j\left(\frac{Q_{ijt}}{\lambda_j^{\gamma_j}\epsilon_{ij}A_{ijt}}\right)\frac{r_{ijt}^{\alpha_j}\left(p_{ijt}^{m}\right)^{\gamma_j}}{w_{ijt}^{\alpha_j+\gamma_j}} \tag{A.4.2}$$

$$M_{ijt} = \gamma_j\left(\frac{Q_{ijt}}{\lambda_j^{\gamma_j}\epsilon_{ij}A_{ijt}}\right)\frac{r_{ijt}^{\alpha_j}w_{ijt}^{\beta_j}}{\left(p_{ijt}^{m}\right)^{\alpha_j+\beta_j}} \tag{A.4.3}$$

$$E_{ijt} = \eta_j\left(\frac{1}{\lambda_j^{1-\eta_J}}\right)\left(\frac{p_{ijt}^{O}}{p_{ijt}^{E}}\right)^{1-\eta_j}M_{ijt} \tag{A.4.4}$$

$$O_{ijt} = (1-\eta_j)\left(\frac{1}{\lambda_j^{1-\eta_J}}\right)\left(\frac{p_{ijt}^{E}}{p_{ijt}^{O}}\right)^{\eta_j}M_{ijt} \tag{A.4.5}$$

A.5 Marginal costs

$$c_{it} = \frac{1}{\mu_i}\left(\sum_{j}\delta_j c_{ijt}{}^{1-\varepsilon}\right)^{\frac{1}{1-\varepsilon}} \tag{A.5.1}$$

$$c_{ijt} = \left(\frac{1}{\lambda_j^{\gamma_j}\epsilon_{ij}A_{ijt}}\right)r_{ijt}^{\alpha_j}w_{ijt}^{\beta_j}\left(p_{ijt}^{m}\right)^{\gamma_j} \tag{A.5.2}$$

$$c_{ijt}^{M} = \left(\frac{1}{\lambda_j^{1-\eta_J}}\right)\left(p_{ijt}^{E}\right)^{\eta_j}\left(p_{ijt}^{O}\right)^{1-\eta_j} \tag{A.5.3}$$

$$c_{ijt} = \left(\frac{1}{\lambda_j^{\gamma_j(1-\eta_J)}\epsilon_{ij}A_{ijt}}\right) r_{ijt}^{\alpha_j} w_{ijt}^{\beta_j}\left(\left(p_{ijt}^{E}\right)^{\eta_j}\left(p_{ijt}^{O}\right)^{1-\eta_j}\right)^{\gamma_j} \tag{A.5.4}$$

A.6 Optimal production

$$\frac{Q_{ijt}}{\left(\sum_j \delta_j Q_{ijt}^{\rho}\right)^{\frac{1}{\rho}}} = \left(\frac{\rho\delta_j c_{ijt}}{\mu_i p_{it}}\right)^{-\varepsilon} \tag{A.6.1}$$

$$Q_{ij't} = \left[\left(\frac{\delta_{j'}}{\delta_j}\right)\left(\frac{c_{ijt}}{c_{ij't}}\right)\right]^{\frac{1}{1-\rho}} Q_{ijt} \tag{A.6.2}$$

A.7 Dynamic conditions

$$r_{ijt}\left(1 + h\left(K_{ijt+1} - K_{ijt}\right)\right) = \frac{1}{1+\vartheta_{t+1}}\,\mathbb{E}_t\left[\alpha_j p_{it+1}\mu_i \frac{Q_{it+1}}{K_{ijt+1}} + hr_{ijt+1}\left(K_{ijt+2} - K_{ijt+1}\right) + r_{ijt+1}(1-\zeta)\right] \tag{A.7.1}$$

$$h_{ijt} = \frac{1}{1+\vartheta_{t+1}}\,\mathbb{E}_t\left[\alpha_j p_{it+1}\mu_i \frac{Q_{it+1}}{O_{ijt+1}} + h_{ijt+1}\left(1 - \mu_{ijt+1}(1-\eta_j)^{\eta_j}\frac{Q_{ijt+1}}{g_{ijt+1}O_{ijt+1}}\right)\right] \tag{A.7.2}$$

Appendix B. Additional results

B.1. Mine Depletion

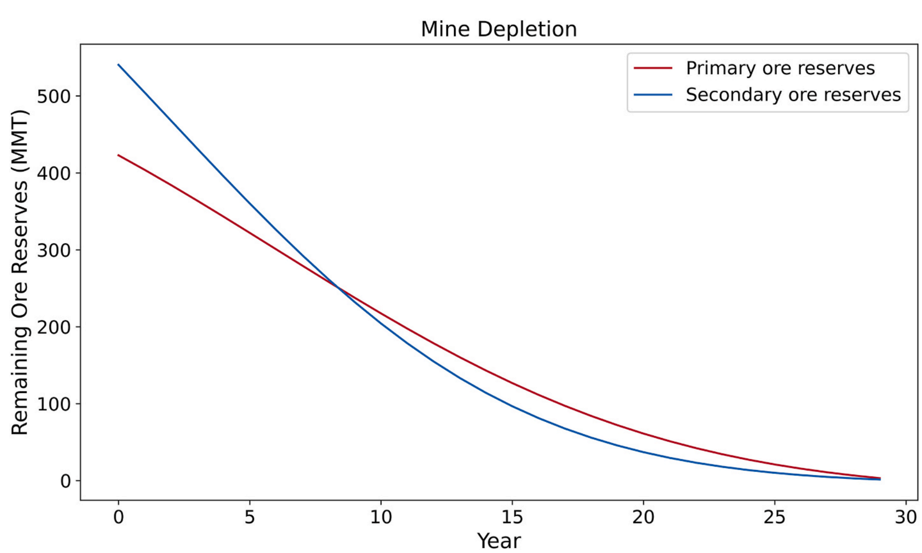

Fig. B.1. Depletion of primary and secondary ore inputs
Notes: The figure shows how the NPV of the overall operation changes with different levels of price volatility for both the primary (left plot) and secondary (right plot) commodities. The NPV with secondary production is slightly higher than business as usual. In the case of primary, only price volatility of iron-ore is modified but everything else is kept constant. While in the case of secondary, only the price volatility of ore-sand is modified.

B.2 Material recovery and processing efficiency

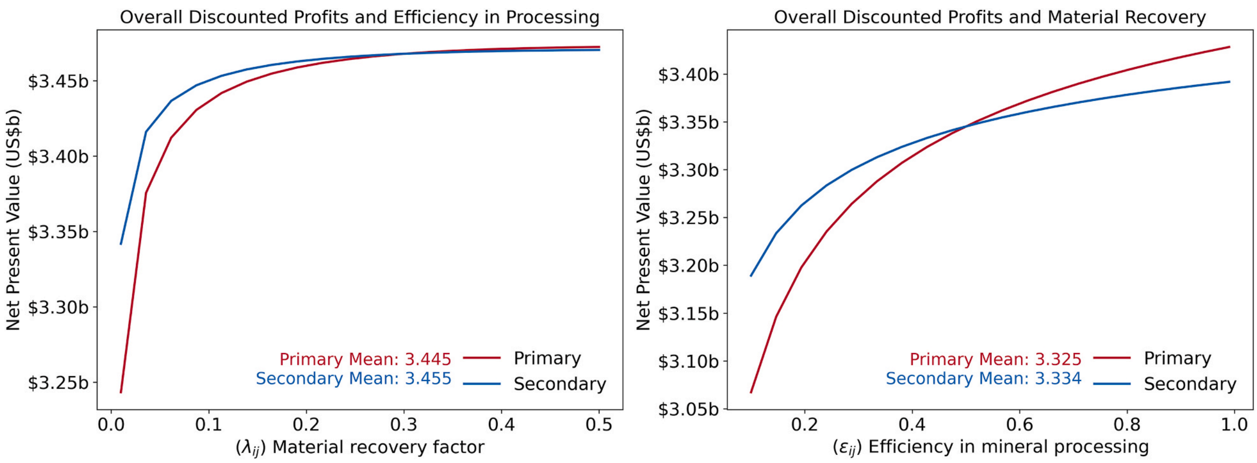

Fig. B.2. Effects of exogenous variations on the material recovered and efficiency in processing
Notes: The Figure demonstrates the effect on the NPV for different values of key parameters in the model, capturing exogenous variation in factors associated with the recovery and processing of minerals and materials. The left plot illustrates the impact of material recovery, while the right plot shows the effects of processing efficiency, reflecting variations in how efficiently the operation processes ore inputs. When the effects of the primary commodity were analyzed, all parameters associated with secondary production were held constant, and vice versa. Due to the relatively small scale of secondary production in relation to primary production, the impact of shocks related to the secondary commodity on the overall discounted profits of the operation were negligible compared to the effects of factors associated with the primary commodity.

B.3 Price volatility of primary and secondary output

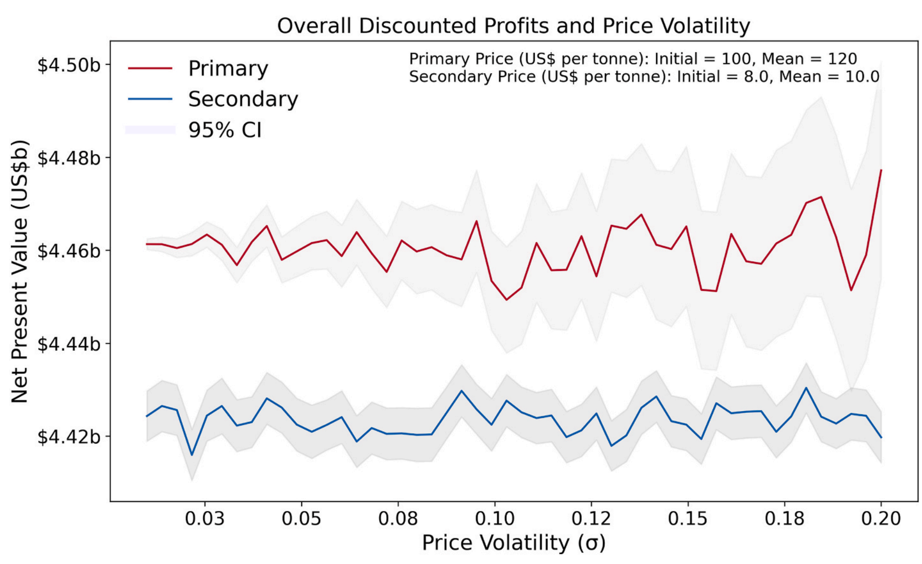

Fig. B.3. Effects of price volatility on the overall discounted profits of the mine
Notes: The figure shows how the NPV of the overall operation changes with different levels of price volatility for both the primary and secondary commodities. In the case of primary, only price volatility of iron-ore is modified but everything else is kept constant. While in the case of secondary, only the price volatility of ore-sand is modified. Results show that higher price volatility had a small effect on increasing the uncertainty of the operation's profitability.

Table B.4
NPV across different growth rates, discount rates, and waste management and rehabilitation costs.

Growth Rate	Discount Rate																			
	2%										4%									
	Waste Management and Rehabilitation Costs																			
	10%	20%	30%	40%	50%	60%	70%	80%	90%	BAU	10%	20%	30%	40%	50%	60%	70%	80%	90%	BAU
1%	2.17	2.02	1.87	1.72	1.56	1.41	1.26	1.11	0.95	0.81	1.60	1.48	1.36	1.25	1.12	1.00	0.89	0.76	0.65	0.54
2%	4.48	4.29	4.16	4.02	3.85	3.71	3.56	3.41	3.25	3.10	3.20	3.08	2.98	2.85	2.73	2.60	2.50	2.37	2.26	2.14
3%	8.25	8.09	7.93	7.77	7.60	7.47	7.31	7.17	7.02	6.87	5.82	5.73	5.58	5.45	5.35	5.23	5.13	4.97	4.89	4.76
4%	14.33	14.17	14.07	13.89	13.71	13.55	13.46	13.31	13.18	12.97	10.00	9.93	9.77	9.66	9.54	9.42	9.32	9.19	9.06	8.94
5%	24.05	23.91	23.71	23.64	23.43	23.27	23.08	22.98	22.90	22.72	16.62	16.51	16.39	16.21	16.19	16.11	15.90	15.80	15.67	15.64

Growth Rate	**Discount Rate**																			
	6%										**8%**									
	Waste Management and Rehabilitation Costs																			
	10%	20%	30%	40%	50%	60%	70%	80%	90%	**BAU**	10%	20%	30%	40%	50%	60%	70%	80%	90%	**BAU**
1%	1.20	1.11	1.01	0.92	0.82	0.73	0.63	0.53	0.44	0.34	0.93	0.85	0.78	0.69	0.62	0.54	0.46	0.38	0.30	0.22
2%	2.37	2.25	2.16	2.06	1.98	1.89	1.79	1.68	1.59	1.49	1.77	1.70	1.61	1.53	1.45	1.38	1.30	1.22	1.14	1.07
3%	4.20	4.11	4.02	3.92	3.82	3.72	3.62	3.54	3.44	3.33	3.09	3.01	2.94	2.85	2.78	2.70	2.62	2.56	2.48	2.39
4%	7.11	7.02	6.93	6.83	6.75	6.64	6.54	6.44	6.37	6.26	5.17	5.08	4.99	4.94	4.87	4.76	4.69	4.63	4.53	4.46
5%	11.69	11.58	11.54	11.38	11.34	11.18	11.12	11.05	10.92	10.83	8.41	8.32	8.24	8.15	8.08	8.01	7.90	7.84	7.76	7.67

Growth Rate	**Discount Rate**																			
	10%										**12%**									
	Waste Management and Rehabilitation Costs																			
	10%	20%	30%	40%	50%	60%	70%	80%	90%	**BAU**	10%	20%	30%	40%	50%	60%	70%	80%	90%	**BAU**
1%	0.74	0.67	0.60	0.54	0.47	0.40	0.34	0.27	0.20	0.14	0.60	0.54	0.48	0.43	0.37	0.31	0.25	0.20	0.14	0.08
2%	1.36	1.29	1.22	1.16	1.10	1.03	0.96	0.90	0.83	0.76	1.07	1.01	0.95	0.90	0.84	0.79	0.73	0.67	0.61	0.56
3%	2.33	2.26	2.21	2.13	2.06	1.99	1.93	1.86	1.80	1.73	1.79	1.73	1.68	1.62	1.56	1.50	1.45	1.39	1.34	1.27
4%	3.84	3.75	3.69	3.63	3.55	3.49	3.42	3.34	3.30	3.22	2.89	2.82	2.77	2.71	2.67	2.60	2.54	2.49	2.43	2.37
5%	6.12	6.06	5.97	5.93	5.85	5.78	5.71	5.65	5.60	5.52	4.56	4.49	4.45	4.38	4.32	4.26	4.19	4.15	4.09	4.04

Note: The table presents the NPVs under different combinations of annual growth rates, discount rates, and waste management and rehabilitation costs. The percentages of waste management and rehabilitation costs are in relation to the BAU scenario (100% waste management and rehabilitation costs). I.e., a 10% waste management and rehabilitation costs in the table describes a scenario in which these costs are reduced 90% in relation to BAU.

Data availability

Data will be made available on request.

References

Abbadi, A., Mucsi, G., 2024. A review on complex utilization of mine tailings: recovery of rare earth elements and residue valorization. J. Environ. Chem. Eng. 12 (3), 1–18.

Aguirregabiria, V., Luengo, A., 2016. A Microeconometric Dynamic Structural Model of Copper Mining Decisions. Unpublished Manuscript. The University of Toronto.

Anderson, J.E., van Wincoop, E., 2004. Trade costs. J. Econ. Lit. 42 (3), 691–751.

Andersson, H., 2007. Are commodity prices mean reverting? Appl. Financ. Econ. 17 (10), 769–783.

Araya, N., Kraslawski, A., Cisternas, L.A., 2020. Towards mine tailings valorization: recovery of critical materials from Chilean mine tailings. J. Clean. Prod. 263, 1–10, 121555.

Armstrong, M., Langrené, N., Petter, R., Chen, W., Petter, C., 2019a. Accounting for tailings dam failures in the valuation of mining projects. Resour. Policy 63 (101461), 1–15.

Armstrong, M., Petter, R., Petter, C., 2019b. Why so many tailings dams failed in recent years? Resour. Policy 63 (101412), 1–11.

Asad, M.W.A., Dimitrakopoulos, R., 2013. A heuristic approach to stochastic cut-ff grade optimization for open pit mining complexes with multiple processing streams. Resour. Policy 38, 591–597.

Bernard, J.-T., Khalaf, L., Kichian, M., McMahon, S., 2008. Forecasting commodity prices: GARCH, jumps, and mean reversion. J. Forecast. 27 (4), 279–291.

Bian, Z., Miao, X., Lei, S., Chen, S., Wang, W., Struthers, S., 2012. The challenges of reusing mining and mineral-processing wastes. Science 337 (6095), 702–703.

Bowker, L.N., Chambers, D.M., 2015. The risk public liability and economics of tailings storage facility failures. Earthwork Act. 24, 1–56.

Brennan, M., Schwartz, E., 1985. Evaluating natural resource investment. J. Bus. 58 (2), 135–157.

Burritt, R.L., Christ, K.L., 2021. Full cost accounting: a missing consideration in global tailings dam management. J. Clean. Prod. 321, 129016.

Carneiro, A., Fourie, A., 2020. Assessing the impacts of uncertain future closure costs when evaluating strategies for tailings management. J. Clean. Prod. 247, 119173.

Castillo, F., Dimitrakopoulos, R., 2014. Joint effect of commodity price and geological uncertainty over the life of mine and ultimate pit limit. Min. Technol. 123 (4), 207–219.

Cortazar, G., Schwartz, E., Casassus, J., 2001. Optimal exploration investments under price and geological-technical uncertainty: a real options model. R D Manag. 31 (2), 181–189.

Cortazar, G., Casassus, J., 1998. Optimal timing of a mine expansion: implementing a real options model. Q. Rev. Econ. Finance 38 (3), 755–769.

Cox, B., Innis, S., Mortaza, A., Kunz, N.C., Steen, J., 2022. A unified metric for costing tailings dams and the consequences for tailings management. Resour. Policy 78 (102862), 1–9.

Da, S., Le Billon, P., 2022. Sand mining: stopping the grind of unregulated supply chains. Extr. Ind. Soc. 10 (101070), 1–12.

de Palacios, L., Espí, J.A., 2022. In mining, not everything is a circular economy: case studies from recent mining projects in Iberia. Resour. Policy 78 (102798), 1–11.

Dimitrakopoulos, R., Abdel Sabour, S., 2007. Evaluating mine plans under uncertainty: can the real options make a difference? Resour. Policy 32, 116–125.

Edraki, M., Baumgartl, T., Manlapia, E., Bradshaw, D., Franks, D.M., Moran, C.J., 2014. Designing mine tailings for better environmental, social, and economic outcomes: a review of alternative approaches. J. Clean. Prod. 84 (1), 411–420.

Elshkaki, A., Graedel, T.E., Ciacci, L., Reck, B.K., 2018. Resource demand scenarios for the major metals. Environ. Sci. Technol. 52, 2491–2497.

Evatt, G.W., Soltan, M.O., Johnson, P.V., 2012. Mineral reserves underprice uncertainty. Resour. Policy 37, 340–345.

Fevereiro, J.B., Genovese, A., Purvis, B., Codina, O.V., Passarella, M.V., 2025. Macroeconomic models for assessing the transition towards a circular economy: a systematic review. Ecol. Econ. 236 (108669), 1–18.

Franks, D.M., 2020. Reclaiming the neglected minerals of development. Extr. Ind. Soc. 7 (2), 453–460.

Franks, D., Boger, D., Côte, C., Mulligan, D., 2011. Sustainable development principles for the disposal of mining and mineral processing wastes. Resour. Policy 36 (2), 114–122.

Franks, D.M., Segura-Salazar, J., Gallagher, L., Habte, L.E., Bioantika, Golev, A., Stringer, M., Rogers, P., Soto-Diaz, J., Ardhanari, M., Antonio, C., Leigh, S., 2025. Nose to tail mining: a circular solution for sand supply and tailings reduction at scale. One Earth 8 (2).

Franks, D.M., Stringer, M., Torres-Cruz, L.M., Baker, E., Valenta, R., Thygesen, K., Matthews, A., Howchin, J., Barrie, S., 2021. Tailings facility disclosures reveal stability risks. Sci. Rep. 11, 1–7, 5353.

Fullerton, D., 2024. The Circular Economy. *NBER Working Paper Series 32419*.

Golev, A., Gallagher, L., Vander Velpen, A., Lynggaard, J.R., Friot, D., Stringer, M., Chuah, S., Arbelaez-Ruiz, D., Mazzinghy, D., Moura, L., Peduzzi, P., Franks, D.M., 2022. Ore-Sand: a potential new solution to the mine tailings and global sand sustainability crises. Final Report. The University of Queensland & University of, Geneva. https://doi.org/10.14264/503a3fd.

González, G., 2022. Commodity price shocks, factor utilization, and productivity dynamics. In: Working Papers of the Central Bank of Chile No. 939.

Goulart Bezerra, C., Abelha Rocha, C.A., Scheibe de Siqueira, I., Toledo Filho, R.D., 2021. Feasibility of iron-rich ore tailing as supplementary cementitious material in cement pastes. Constr. Build. Mater. 303 (124496), 1–10.

Gross, I., Hansen, J., 2013. Reserves of Natural Resources in a Small Open Economy. Reserve Bank of Australia Research Discussion Paper 2013-14.

Haque, Md A., Topal, E., Lilford, E., 2014. A numerical study for a mining project using real options valuation under commodity price uncertainty. Resour. Policy 39, 115–123.

Hudson-Edwards, K.A., Kemp, D., Torres-Cruz, L.A., Macklin, M.G., Brewer, B., Owen, J. R., Franks, D.M., Marquis, E., Thomas, C.J., 2024. Tailings storage facilities, failures and disaster risk. Nat. Rev. Earth Environ. 5, 612–630.

Hund, K., La Porta, D., Fabregas, T.P., Laing, T., Drexhage, J., 2020. Minerals for Climate Action: the Mineral Intensity of the Clean Energy Transition. The World Bank, Washington, DC.

ICMM, 2020. Global Industry Standard on Tailings Management. International Council on Mining and Metals, London, UK.

ICMM, 2024. Tools for Circularity. International Council on Mining and Metals, London, UK.

Kinnunen, P., Karhu, M., Yli-Rantala, E., Kivikkyto-Reponen, P., Makinen, J., 2022. A review of circular economy strategies for mine tailings. Clean. Eng. Technol. 8 (100499), 2–13.

Kinnunen, P.H., Kaksonen, A.H., 2019. Towards circular economy in mining: opportunities and bottlenecks for tailings valorization. J. Clean. Prod. 228, 153–160.

Labonne, B., 2016. Mining dam failure: business as usual? Extr. Ind. Soc. 3 (3), 651–652.

Lèbre, É., Corder, G.D., Golev, A., 2017a. Sustainable practices in the management of mining waste: a focus on the mineral resource. Miner. Eng. 107, 34–42.

Lèbre, É., Corder, G.D., Golev, A., 2017b. The role of the mining industry in a circular economy: a framework for resource management at the mine site level. J. Ind. Ecol. 21 (3), 662–672.

Lottermoser, B.G., 2011. Recycling, reuse, and rehabilitation of mine wastes. Elements 7, 405–410.

Measham, T., Walker, J., Haslam McKenzie, F., Kirby, J., Williams, C., D'Urso, J., Littleboy, A., Samper, A., Rey, R., Maybee, B., Brereton, D., Boggs, G., 2024. Beyond closure: a literature review and research agenda for post-mining transitions. Resour. Policy 90, 104859.

Mendes Protasio, F.N., Ribeiro de Avillez, R., Letichevsky, S., de Andrade Silva, F., 2021. The use of iron ore tailings obtained from the Germano dam in the production of a sustainable concrete. J. Clean. Prod. 278 (123929), 1–17.

Nassar, N.T., Lederer, G.W., Brainard, J.L., Padilla, A.J., Lessard, J.D., 2022. Rock-to-metal ratio: a foundational metric for understanding mine wastes. Environ. Sci. Technol. 56 (10), 6710–6721.

Ndlovu, S., Simate, G.S., Matinde, E., 2017. Waste Production and Utilization in the Metal Extraction Industry. CRC Press, Boca Raton, CA.

Nogueira, M., 2023. Brazil's vale creates company to sell sand from iron ore tailings. Reuters. Retrieved from: https://www.reuters.com/markets/commodities/brazils-vale-creates-company-sell-sand-iron-ore-tailings-2023-10-17/.

Nogueira, M., 2024. Vale sees 10% of its iron ore production coming from tailings by 2030. Reuters. Retrieved from. https://www.reuters.com/markets/commodities/vale-sees-10-its-iron-ore-production-coming-tailings-by-2030-2024-09-12/.

Packey, D.J., 2012. Multiproduct mine output and the case of mining waste utilization. Resour. Policy 37, 104–108.

Piciullo, L., Storrøsten, E.B., Liu, Z., Nadim, F., Lacasse, S., 2022. A new look at the statistics of tailings dam failures. Eng. Geol. 303 (106657), 1–14.

Priester, M., Ericsson, M., Dolega, P., Lof, O., 2019. Mineral grades: an important indicator for environmental impact of mineral exploitation. Min. Econ. 32, 49–73.

Redlinger, M., Eggert, R., 2016. Volatility of by-product metal and mineral prices. Resour. Policy 47, 69–77.

Rimélé, M.A., Dimitrakopoulos, R., Gamache, M., 2018. A stochastic optimization method with in-pit waste and tailings disposal for open pit life-of-mine production planning. Resour. Policy 57, 112–121.

Rimélé, M.A., Dimitrakopoulos, R., Gamache, M., 2020. A dynamic stochastic programming approach for open pit mine planning with geological and commodity price uncertainty. Resour. Policy 65 (101570), 1–8.

Savolainen, J., 2016. Real options in metal mining project valuation: review of literature. Resour. Policy 50, 49–65.

Schwartz, E., 1997. The stochastic behavior of commodity prices: implications for valuation and hedging. J. Finance 52 (3), 923–973.

Segura-Salazar, J., Ekubatsion, L.H., Serati, M., Dao, V., Gravina, R., Antonio, C., Walker, S., Zhu, X., Vollert, L., Seaman, D., Asche, H., Franks, D.M., 2026. Evaluating ore-sand by-products at Cadia's porphyry copper-gold mine for construction applications. Miner. Eng. 237. https://doi.org/10.1016/j.mineng.2025.110001.

Segura-Salazar, J., Franks, D., 2023a. Is ore-sand the solution to the mining industry's waste problem? Min. Mag. 32–34.

Segura-Salazar, J., Franks, D., 2023b. Ore-Sand co-production from Newcrest's Cadia east HydroFloat Reject: an Exploratory Study. The University of Queensland. https://doi.org/10.14264/96249f6.

Sulista, S., Rosyid, F.A., Wibowo, A.P., 2023. Turning waste into profit: circular economic optimization of quartz sand from tin mining and processing. Sustain. Prod. Consum. 39, 53–62.

Suppes, R., Heus-Aßbichler, S., 2021. Resource potential of mine wastes: a conventional and sustainable perspective on a case study tailings mining project. J. Clean. Prod. 297 (126446), 1–15.

Tang, L., Werner, T.T., 2023. Global mining footprint mapped from high-resolution satellite imagery. Nat. Commun. Earth Environ. 4 (134), 1–12.

Thompson, M., Barr, D., 2014. Cut-off grade: a real options analysis. Resour. Policy 42, 83–92.
UNEP, 2022. Sand and Sustainability: 10 Strategic Recommendations to Avert a Crisis. GRID-Geneva, United Nations Environment Programme, Geneva, Switzerland.
Vale, 2022. Vale expands production of sustainable sand in Brazil. Retrieved from. https://vale.com/w/vale-expands-production-of-sustainable-sand-in-brazil.
Vale, 2023. Vale launches company to develop sustainable sand business. Retrieved from. https://vale.com/w/vale-launches-company-to-develop-sustainable-sand-business-2.
Valenta, R.K., Lèbre, É., Antonio, C., Franks, D.M., Jokovic, V., Micklethwaite, S., Parbhakar-Fox, A., Runge, K., Savinova, E., Salazar-Segura, J., Stringer, M., Vester, C., Yahyaei, M., 2023. Decarbonisation to drive dramatic increase in mining waste–options for reduction. Resour. Conserv. Recycl. 190, 106859.
Valentine, S.V., 2024. Putting the 'economy' back in the circular economy. Bus. Strat. Environ. 33 (7), 6221–6234.
van der Ent, A., Parbhakar-Fox, A., Erskine, P.D., 2021. Treasure from trash: mining critical metals from waste and unconventional sources. Sci. Total Environ. 758 (143673), 1–3.