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Perspective

Global Scan of Disruptions to the Mine Life Cycle: Price, Ownership, and Local Impact

Éléonore Lèbre,* John R. Owen, Martin Stringer, Deanna Kemp, and Rick K. Valenta

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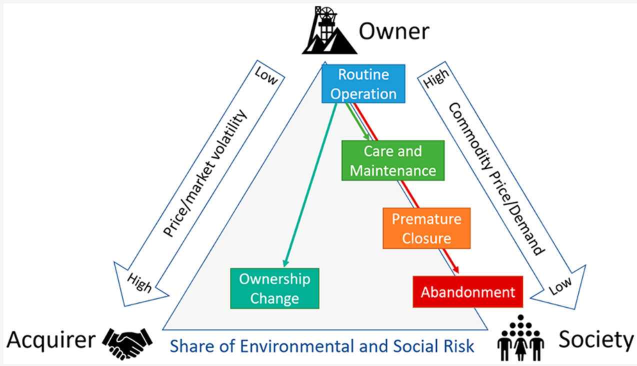

ABSTRACT: Criticality and supply risk models seek to address concerns of potential disruption to global metal supply. These models need to incorporate disruption events that arise from within the mining industry's market structure. In this paper, we review what we refer to as events of "mine life cycle disruption". These include project abandonments, premature closures, care and maintenance, and ownership changes. Life cycle disruptions not only cause production disruptions but also embed social and environmental risks in global metal markets. They arise from the highly variable business environment in which the resources sector operates. Changing commodity prices directly influence mining revenues and drive decisions on whether to halt or push forward a project. While some disruptions are involuntary and induced by external economic conditions, others are purposefully triggered by certain mining companies that use them to their advantage. We examine the frequency of these disruptions based on a contemporary global inventory of 35,000 mining projects and present the findings against recent developments in the research literature. We conclude that life cycle disruption events are an important consideration in balancing the demand for metals and the social and environmental impacts of mining and propose pathways for managing these events and their effects.

Society's needs for metals are increasing[1,2] as the key material inputs required to drive the energy transition[3,4] and to achieve broad-based human development goals.[5] These growing needs lead to two types of concerns. The first is about the accessibility of mineral resources and the risk of production being constrained, resulting in a disruption to supply.[6] The prevailing view is that disruptions are more likely to arise from a combination of man-made factors rather than purely geological factors.[7,8] The second type of concern is about sustainable development and the social and environmental implications of resource extraction.

Extensive research has sought to address these concerns. The criticality literature assesses both the risk of supply disruption and the environmental impacts embedded in the supply chain for specific metal commodities. Here supply risk is based on the countries in which mineral reserves are located. Criticality assessments have been applied to evaluate the likely impact of political decisions on the global supply of metals, such as China's rare earths policy[9] or the ban on nickel ore exports in Indonesia.[10] In consumer countries, such as the United States and countries of the European Union, these methodologies are a means of identifying actions that would secure minerals that are critical to their economy, e.g., refs 11−13. Meanwhile, producing countries and mining companies are seeking to reinforce their position as reliable suppliers of critical minerals.[14]

Continuing methodological advancements enhance the detail in the criticality assessment approach. Recent research disaggregates the supply source into multiple geo-located extractive sites. This provides the basis for analyzing the geographic, social, political, and environmental context in which the geological resource is located. This approach encompasses both questions of supply risk and the implications for host communities and environments. First, it enables the identification of production disrupting events, with the understanding that concurrent events at multiple source sites will have ramifications on global supply.[15] Second, the spatial analysis identifies factors of vulnerability within the host context that determine the type and extent of impacts generated by mining activities. Studies establish a link between production disruption events and complex environmental,

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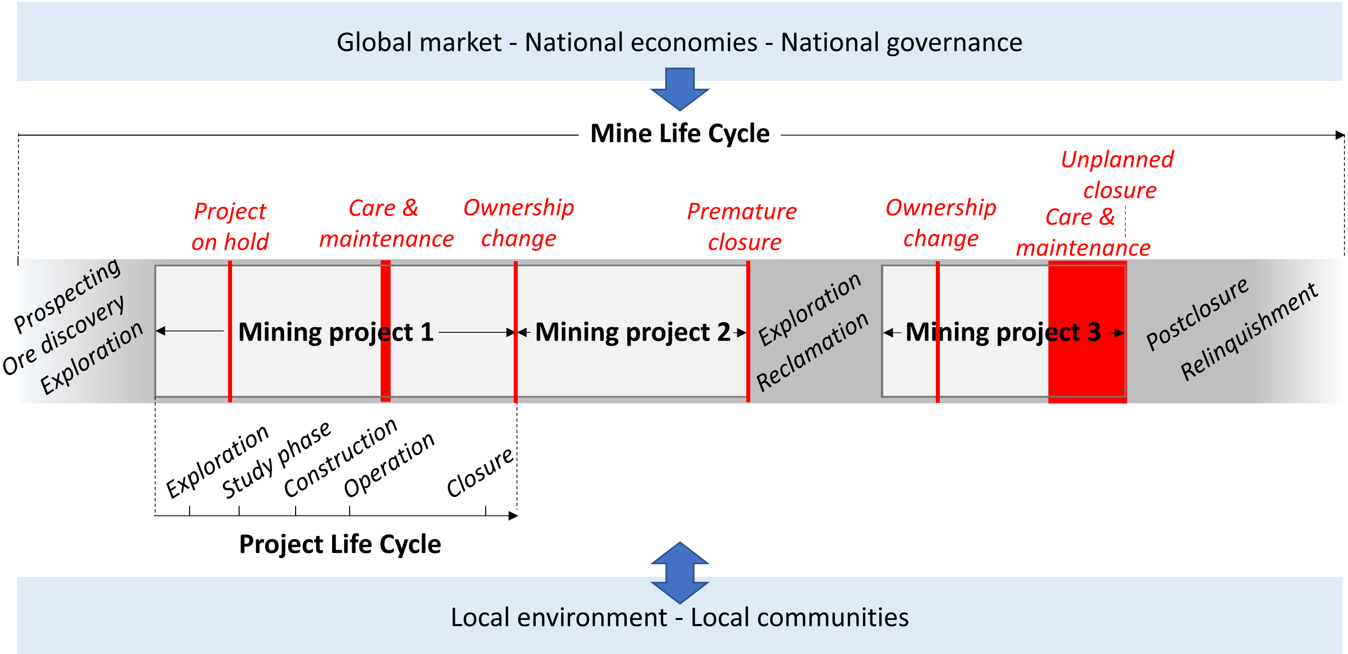

Figure 1. Disruptions in the mine life cycle and the extractive system.

social, and political settings.[16,17] They suggest that increases in mining-related conflicts[18] and environmental disasters[19] could further exacerbate future supply risks.

While recent works assess the national and local contexts of resource development projects, they do not examine internal industry factors. In this paper, we examine causes of production disruption that arise from within the mining industry's market structure. These causes lead to what we refer to as events of "mine life cycle disruption". Events include project abandonments, premature closures, care and maintenance, and ownership changes. They are common and create discontinuities in the mine life cycle, which negatively affect production output and embed social and environmental impacts into the supply chain. One key driver of production disruption is the commodity market, with fluctuating prices and investor support, shaping both capital investment and local operational decisions. Another driver is short-term decision-making, including timeframes for innovation.[20] Short-term decision-making aims to minimize financial risk but can increase risk factors in other domains (e.g., social and environmental).[21] From this perspective, the industry's market structure can enhance our understanding of supply dynamics.

In the next section, we examine the frequency of mine life cycle disruption events based on a contemporary global inventory of 35,000 mining projects and present the findings against recent developments in the research literature. In the section that follows, we comment on the industry's market structure where the drivers of disruption are found. Finally, we elaborate on the implications for future global mineral supply, considering both supply risk and embedded impacts. We conclude by proposing pathways for managing these disruptions and their effects.

■ COMMON FORMS OF DISRUPTION IN THE MINE LIFE CYCLE

Figure 1 represents the extractive system, centered on the mine life cycle. The mine life cycle is typically made of one or several extractive projects, as well as additional stand-alone activities. Disruptions (in red) can occur at any stage of the life cycle with varying duration, drivers, causes, and consequences. Elements of Figure 1 are explained throughout the text, starting in this section with the different types of disruption. These are categorized as (i) unplanned and premature closures, (ii) inactive projects, (iii) projects on hold or in care and maintenance, and (iv) changes in ownership.

For each type of disruption, we analyzed data from one of the largest repositories of mining project data, the S&P Global Market Intelligence database (the S&P database). This data set gathers public reports on more than 35,000 mining projects worldwide. Fields relevant to this study are activity status, development stage, and current and historical ownership details. We analyzed these fields and relate them to key observations from the literature.

Unplanned and Premature Closures. Evidence suggests that mine closures often occur prematurely, before the mineral resource is depleted. Premature closure is a mine life cycle disruption as it interrupts production and leads to suboptimal extraction outcomes. It is a concern for governments who have a responsibility to ensure that the national resource endowment provides maximum value for the country and its citizens. Our review of over 1,800 records of closed mines in the S&P database shows that 17% still have declared mineral reserves.[22] This accounts for approximately 9 billion tonnes of unextracted ore worldwide and USD 2,700 billion of in situ value. Estimates of ore tonnage and in situ value are subject to uncertainties and are valid under specific market conditions. At the individual project level, closure may have been deemed timely given current market conditions. On a global scale, however, these numbers are likely to be underestimated due to the low level of disclosure in the S&P database. For comparison, only 53% of mining projects reported as "operating" in the S&P database have recorded reserves, and the average ore tonnage (reserves only) per operating project is about 200 million tonnes. If the disclosure rate were consistent across the S&P database, the amount of ore reserves left behind after closure could be in the order of 17 billion tonnes.

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These findings signal potential opportunities for further economic extraction at prematurely closed mine sites. It further suggests that mine closures are not strictly driven by the orebody. Our analysis of global data confirms that mine reopenings are frequent. Spatial overlay between the S&P database and the Fineprint data set,[23] which contains georeferenced polygons of mining areas, shows that 834 preproduction projects fall into an existing mine footprint. These "brownfield" projects account for USD 4,500 billion in in situ value, and 60 billion tonnes of reserves and resources. While some of these projects may reach production, it is likely that significant opportunities for economic extraction will be lost as reopening a mine after closure requires significant capital investment. Premature closures are a form of production disruption that can result in resource sterilization, meaning the material that could have been extracted offers no immediate or future economic value.

Previous research has highlighted the negative impacts of premature closures on the host context. This is because premature closures often coincide with deficiencies in closure planning. A closure plan should provide for environmental rehabilitation and include a strategy to manage socioeconomic transitions to a postclosure state.[24−26] An unplanned closure means that impact mitigation strategies have not been implemented according to an agreed plan or schedule.[25,27,28] Unplanned or poorly planned mine closures are significant disruptions that can negatively impact the workforce, communities, and the environment. A review of 1000 mine closure events over a 30-year period confirms that premature and/or unplanned closures are frequent, representing 75% of the identified events.[29]

Inactive Mining Projects. Uncertainty increases when mine closures are not formally recorded. The S&P database records the operational status of mining projects around the world. The number of "inactive" projects—projects where all development activities have ceased—is concerning. In April 2020, 60% of all mining projects recorded in the S&P database (21,195 records) were listed as "inactive" (Figure 2). This suggests that "inactivity" in the mining industry is more common than "activity". Only 8% of these inactive projects are also listed as closed, the remaining 92% are either early stage projects (early stages are categorized in Figure 2 as grass roots, exploration, target outline, reserves development, feasibility, and preproduction) or in operation. Inactivity is common in early stage projects, which contain the minerals that will define future supply.[17] When considering only projects that have declared reserves or resources, we find that 46% (roughly 3,000 projects) of these early stage projects are inactive. These projects account for 373 billion tonnes in reserves and resources and 33,000 billion dollars of in situ value, approximately one-third of all early stage reserves and resources. There can be multiple reasons why these projects ceased activity, including low commodity prices, lack of funding, permitting issues, or community opposition. As nonrevenue generating assets, early stage projects are particularly vulnerable to disruption.

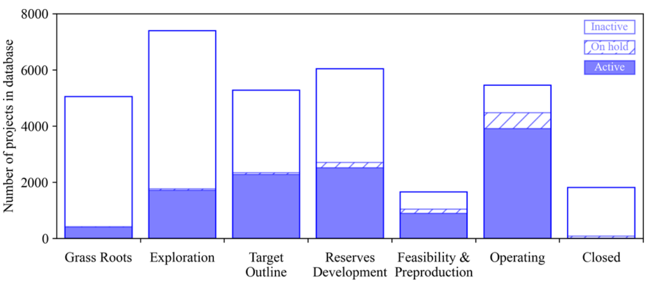

Figure 2. Distribution of 35,320 mining projects by development stage and activity status. The "on hold" status category covers temporary suspensions in activity and instances of care and maintenance. Data was compiled from S&P Global Market Intelligence.

Projects that are "inactive" at the operational stage are less common (18%), but the potential consequences of inactivity are high. Once a project passes the construction stage, project-induced changes in local communities and environment can be irreversible, and social and environmental impact programs become paramount to ensure negative impacts are managed and mitigated. As an indication of the scale of the footprint, about 40% of 1000 inactive operations are open cut mines, containing on average 80 million tonnes in reserves and resources. This corresponds to a medium-size copper mine. In terms of economic value, inactive operations represent 5,000 billion dollars of in situ value. Projects with an inactive status are more likely to be abandoned, which can result in significant social and environmental legacies being transferred to the State. The Queensland state government in Australia, for example, has prioritized the management of 120 large abandoned mine sites with a combined land disturbance area of 10,300 ha.[30] Mine abandonment significantly decreases the chances of successful rehabilitation and can leave local communities in limbo.[31] The inactivity status is therefore consequential, as it both disrupts production and compromises the management of social and environmental impacts.

Care and Maintenance. The proportion of operating projects reported as temporarily on hold or in care and maintenance in the S&P database is above 10%, which is likely to be an underestimation that does not capture short-term interruptions and underdisclosed sites. Care and maintenance means that the mine is no longer operating, but an entity maintains the site, infrastructure, and equipment. A 2017 analysis conducted by the state of Queensland's Department of Natural Resources, Mines and Energy[32] revealed that 16% of the State's 170 largest coal, base metal, and precious metal operations were in care and maintenance. An Australia-wide analysis, taken at the end of a mining downturn period in 2016, identified a minimum of 206 mines in care and maintenance,[33] which would correspond to more than 30% of Australian projects at the mining stage in the S&P database. These estimates provide a snapshot of a phenomenon that can take place at any time over the life of a mining operation. Governments are cautious about mining projects moving into care and maintenance, with the move considered an early indicator of abandonment by the operator.[32,34] Sustained periods of care and maintenance threaten long-term economic viability of the asset as it effectively halts production while maintaining fixed costs. During care and maintenance periods, activity levels and number of people on site are brought to a minimum, and social and environmental programs are frequently cut. The longer the interruption, the higher the risk of subsequent closure.[32] An example is the Mount Lyell copper mine in Australia, which has been in care and maintenance for the past seven years following two critical incidents in the later part of 2013. This change in activity status also coincides with a major slump in the global copper

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price. Since 2013, activities on site have been limited to monitoring the tailings storage facility and pumping water out of the underground workings in order to safeguard access to the orebody in case operations resume. The acidic water is being discharged, mainly untreated, into the local river.

Change in Ownership. In contrast to abandonment, a change in ownership may seem inconsequential, but it can be taken as a proxy for how consistently an operation manages the issues associated with its footprint. The S&P database records approximately 6,500 changes in ownership between 2010 and 2020 across the 10,820 projects that have ownership records over this period. Thirty-one percent of these mining projects have had one change in ownership across the 10-year period. Twelve percent have had two changes or more. These numbers do not account for merger and divestment events that occur under the same owner name (for example, Rio Tinto and Newmont both owned the Lihir project in Papua New Guinea under the same subsidiary name "Lihir Gold", before it was sold to Newcrest in 2010).

Ownership changes often lead to disruptions in the operating context. They can result in significant shifts in the extractive strategy, for example, when a copper mine is converted to a gold mine because the new owner has expertise in gold extraction. Ownership changes are often felt by host communities as the new management implements new land acquisition strategies, labor contracts, community engagement programs, and procurement approaches. At the Sepon copper and gold mine in Laos, six ownership changes have been observed between 2000 and 2019. Each successive change in ownership has resulted in a period of expedited growth and a heightened demand for land. The periodic developments have manifested in incremental patterns of population displacement that have progressively eroded ecosystem services and ultimately livelihoods.[35,36] At the La Granja project in Peru, exploration programs were undertaken by three separate companies, which led to three separate relocation exercises. Each effort at displacement directly followed a change in the ownership of the project.[35] Inconsistent resettlement strategies result in exacerbated risks to people, especially given that the industry generally lacks the capability to mitigate the adverse impacts experienced by displaced communities.[37]

In the worst cases of ownership change, "inherited" social and environmental commitments are not carried by the new owner.[38] At the Mount Morgan gold mine in Australia, rehabilitation plans were dropped as a new owner took over in 1982. The site went through four more changes in ownership until 1990, when the mine closed prematurely due to technical difficulties and low gold prices.[39] This example is illustrative of some companies selling aging or problematic assets to avoid the costs and liabilities of closure. While the S&P database does not record such behavior, high rates of ownership changes are a red flag. Recent literature indicates that this particular cost avoidance tactic is commonplace.[33,34,40,41] The Responsible Mining Foundation advocates for thorough due diligence in cases of ownership transfer to ensure social and environmental legacies are known and accounted for.[25] Some jurisdictions are tightening conditions around ownership changes to avoid incurring large unfunded closure and abandonment legacies.[42]

■ RETURNING TO THE MACROECONOMIC ROOTS OF DISRUPTION

Roots of mine life cycle disruptions are found in the extractive industry's market structure. The resources sector operates in a highly variable business environment where commodity prices move through boom-and-bust cycles. Commodity prices directly influence mining revenues and are a key consideration in deciding whether to halt or push forward a project. The peak in ownership changes observed in 2015 (Figure 3)

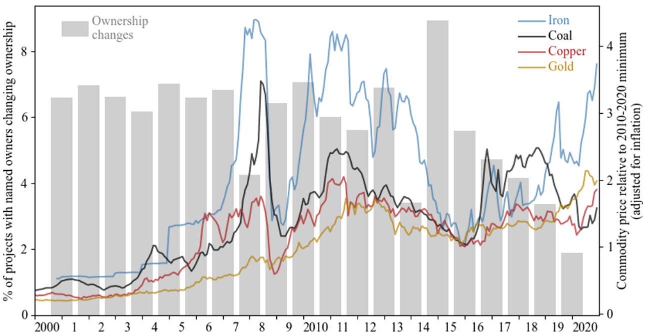

Figure 3. Yearly changes in ownership across a 10,820 project sample, compared with prices for four commodities. Prices are adjusted for inflation using the US consumer price index and normalized to the 2010−2020 minimum price. Data was compiled from S&P Global Market Intelligence.

follows a consistent fall in commodity prices in the preceding few years, including for coal, copper, gold, and iron. During that year, large mining companies Alpha Natural Resources, BHP, and Glencore faced, respectively, the following: bankruptcy, a major demerger event with South32, and a debt reduction plan that resulted in divestment of 44 assets. Miners are "price-takers", meaning they have a low level of influence in determining the market price for their products. The arrows in the top third of Figure 1 show the one-sided influence. Against volatile commodity prices, care and maintenance can be considered a legitimate response when market conditions hinder long-range planning.[32] If unfavorable economics persist, project abandonment, divestment, or a planned closure may ensue. The global market is a key influencer in project-related decisions, which are the direct cause of life cycle disruptions.

The industry responds to changing market conditions with adaptive strategies. While some disruptions are involuntary and induced by external economic conditions, others are purposefully triggered by the mining company. On the one hand, life cycle disruptions can be caused by a company experiencing financial difficulties preventing them from maintaining life cycle continuity. On the other hand, certain companies thrive in a changing environment and use disruptions to their advantage. Strategies like divestment offer an escape from costly social and environmental legacies.[43] In extreme cases, project abandonment leaves the entire legacy to the local context and the host State.[44] This usually happens in jurisdictions that lack the regulatory instruments to prevent or penalize such behavior. However, even mature mining jurisdictions have loopholes that allow mining companies to avoid responsibility.[45,46] The S&P data does not yield information on the scale of voluntary and avoidable disruptions; however, in the absence of effective regulatory safeguards (a pattern often noted in the literature, e.g., refs 34,

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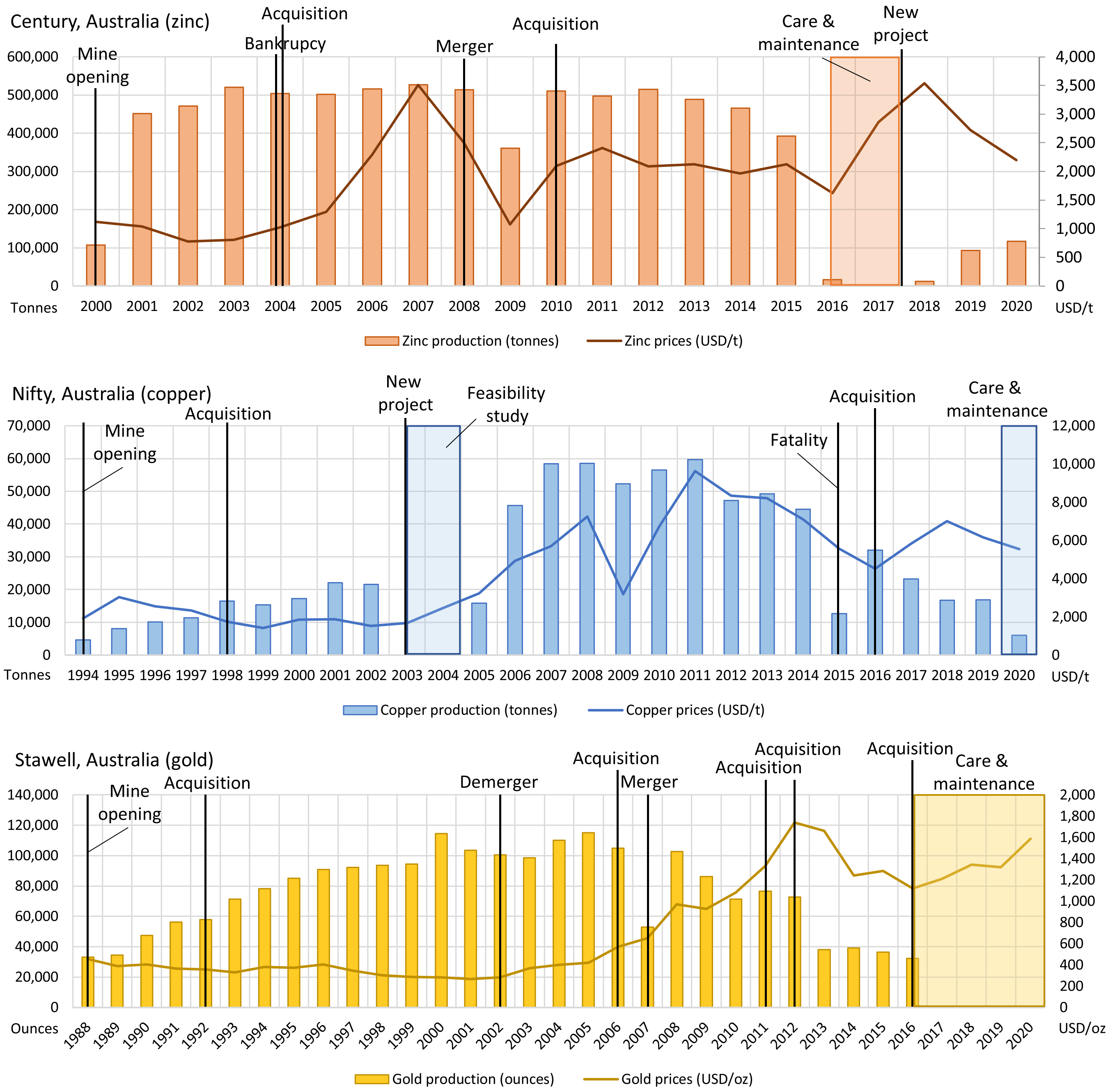

Figure 4. Three examples of mine life cycles.

40, 47, and 48), one can assume that mining companies would seize opportunities for cost minimization.

Figure 4 shows three mine life cycles that exemplify the relationship between global commodity prices, production rates, project status, and life cycle events. Over a 20-year period, each site witnessed several ownership changes, periods of care and maintenance, and, in the case of Century and Nifty, the development of an additional mining project. Care and maintenance coincides with a fall in the commodity price, while a ten-year rise in gold prices resulted in successive acquisitions at the Stawell mine. These observations are prompts for possible inconsistencies in the management of the mine's social and environmental footprint. From this vantage point, production rates can be used as a proxy for the impact profile of the mine, based on the social and environmental stressors induced by the resource extraction process. Activity and ownership status, on the other hand, indicate potential discontinuities in an organization's capability to plan and manage that impact profile.

IMPLICATIONS FOR FUTURE GLOBAL MINERAL SUPPLY

Rather than singular and continuous, we show how mine life cycles can be a disjointed suite of projects interrupted by disruptions. Several projects occurring over the mine life cycle under different owners or operators can mean different extractive plans, production processes, closure plans, and community engagement programs. At the local level, the host environment is shaped by these changes and their implications on the mine footprint.[28] At the global level, high inactivity

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rates across particular commodities could pose supply challenges. Figure 5 shows that proportions of inactive projects

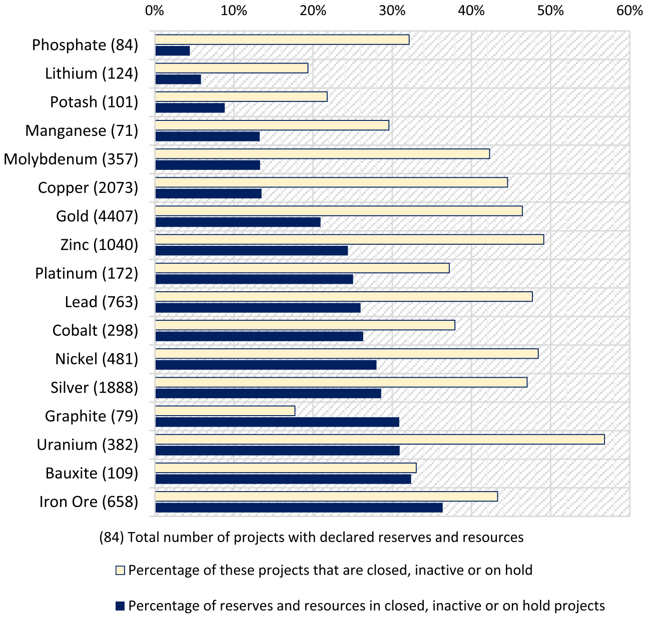

Figure 5. Inactivity patterns across 17 metal and mineral commodities. Sample size: 7,780 mining projects with records on the amount of contained commodity in reserves and resources.

and reserves and resources locked in inactive projects vary widely across commodities. A small strategic sector like graphite (79 projects) may be at risk with predicted high demand growth and a high proportion of reserves and resources locked in inactive, closed, or on hold projects.

Disruptions and discontinuities in the mine life cycle also affect the extractive process itself and result in significant inefficiencies and wastage.[39] They likely result in a suboptimal resource efficiency, i.e., higher energy, water, land, and resources inputs by unit of output. Life cycle disruptions not only cause a direct drop in production but also impede future production through inefficient extractive processes. Few studies examine the role of life cycle disruptions on resource efficiency (e.g., ref 39).

The local context in which mining takes place is the primary repository of mining-induced social and environmental impacts. The frequency of life cycle disruptions constrains miners and regulators in their ability to mitigate these impacts. Mining activities are known to cause significant disturbance to people and the environment, and global mineral supply carries the embedded impacts of mineral extraction.[49,50] The patterns of disruption discussed here can exacerbate these impacts by affecting the continuity and coherence of social and environmental impact management plans at the mine site level. In particular, life cycle disruptions where owners default on their responsibility to rehabilitate the site are leaving negative environmental legacies. Mount Morgan in Australia and Panguna in Papua New Guinea are notorious examples of prematurely closed and abandoned mine sites where rehabilitation was never completed and toxic effluents continue to contaminate waterways, tens of kilometers outside project boundaries.

In certain circumstances, the local context turns into a potential new source of disruption. The risk-rebound dynamics between a mine and its context are well documented, e.g., refs 51 and 52, and visualized by the double-sided arrows in the bottom third of Figure 1. Global studies[16,29] identify disruptions triggered by contextual factors, including natural disasters, labor disputes, and government instability. Examples of community-led disruption are similarly easy to find, e.g., ref 15. Major community opposition at Yanacocha in Peru suspended a fully permitted, multibillion dollar mining project for years. Road blockades at Las Bambas in Peru and Didipio in the Philippines halted the shipment of mineral concentrate for months and effectively forced the two large-scale mining projects into care and maintenance. Oppositional media has resulted in asset divestment from companies looking to safeguard their reputation, further disrupting the mine life cycle.[53] In many jurisdictions, risk rebound dynamics have impacted both the project and host environment, including escalation into full-scale conflict.[54] Frequent disruptions in the mine life cycle constrain project owners in their ability to anticipate and respond to risks emanating from the local context.

■ CONCLUSION

Our findings reveal the type, frequency, and drivers of life cycle disruption events. Life cycle disruptions not only stress the supply chain at the source of production but also embed social and environmental risks in the global metals market. We conclude that life cycle disruption events are an important consideration in balancing the demand for metals and the social and environmental impacts caused by mining. This is a core challenge in international standards where life cycle factors are not well recognized or addressed, e.g., refs 55−57. Similarly, these factors are not integrated into the wide ranging discussions about the industry's contribution to the UN SDGs[58] or climate change mitigation.[59]

Life cycle disruptions are inherent to the mining industry's market structure, and commodity prices will likely remain a major influencer of mining development. However, the corporate response could be better managed to reduce life cycle disruptions and their effects on the host context. International standards and policy guidance on responsible mine closure rely on companies working against their own self-interest. This has proven ineffective.[40,41,47,48] New approaches are needed to better manage the metal supply and limit the negative effects of disruption at the source. For example, States could play a more active role in managing the resource's value to fund life cycle liabilities. Given the high rate and the ultimate cost of life cycle disruptions (particularly abandonment), the ring-fencing part of this value could be a game changer. Reserving value would avoid the situation where project liabilities exceed their economic cost.[60] Policies requiring progressive rehabilitation through the life of mine contribute to reducing end-of-life rehabilitation liabilities;[61] however, they are not enough to prevent abandonment.

This paper has highlighted that mine life cycle disruptions exacerbate social and environmental impacts and generate high uncertainties as to the future of the mine and its host context. Future research about risks in global metal supply should better consider these disruption patterns that are inherent to the mining industry. With greater awareness, the frequency of life cycle disruptions, their duration, and consequences—including risk rebound effects—could be better managed. Researchers need to develop risk models that account for a fuller range of risks at the source of supply. This would better

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recognize that mining projects evolve through a complex interaction between market structure-based risks and context-based risks, in addition to the more traditional geological and technical sets of risks. This will be an important step toward ensuring a reliable and sustainable raw material supply.

AUTHOR INFORMATION

Corresponding Author

Éléonore Lèbre − *Centre for Social Responsibility in Mining, Sustainable Minerals Institute, The University of Queensland, Brisbane, Queensland 4072, Australia;* orcid.org/0000-0002-5159-3446; Email: e.lebre@uq.edu.au

Authors

John R. Owen − *Centre for Social Responsibility in Mining, Sustainable Minerals Institute, The University of Queensland, Brisbane, Queensland 4072, Australia*

Martin Stringer − *W.H. Bryan Mining & Geology Research Centre, Sustainable Minerals Institute, The University of Queensland, Brisbane, Queensland 4072, Australia*

Deanna Kemp − *Centre for Social Responsibility in Mining, Sustainable Minerals Institute, The University of Queensland, Brisbane, Queensland 4072, Australia*

Rick K. Valenta − *W.H. Bryan Mining & Geology Research Centre, Sustainable Minerals Institute, The University of Queensland, Brisbane, Queensland 4072, Australia*

Complete contact information is available at: https://pubs.acs.org/10.1021/acs.est.0c08546

Notes

The authors declare no competing financial interest.

Biography

Dr. Éléonore Lèbre is a Research Fellow at the Sustainable Minerals Institute (SMI) at the University of Queensland (UQ) in Australia. She currently works as part of the Complex Orebodies Programme, which fosters research collaboration across the SMI's environmental, social, and production centers. Her research centers on using global spatially explicit data to develop a multidisciplinary understanding of risks related to mineral resource extraction. She connects this work with topical issues such as the low-carbon energy transition, critical metal supply, and tailings dam failures. Dr. Lèbre contributes to industry research consortia on mining-induced resettlement and the social aspects of mine closure. She brings her expertise to research projects funded by industry partners including Rio Tinto, Newcrest, MMG, and OceanaGold. Dr. Lèbre has a Ph.D. in Industrial Ecology. Her thesis focused on circular economy initiatives in the mining industry, following objectives of waste minimization and resource efficiency. She holds two MSc degrees from the Norwegian University of Science and Technology and the Ecole Centrale Marseille in France, through the Top Industrial Managers in Engineering (TIME) association's double degree arrangements.

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