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Mining industry risks, and future critical minerals and metals supply chain resilience in emerging markets

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ABSTRACT

The mining industry is at a crossroads with the growing demand for exploration and exploitation of critical minerals for the energy transition to reverse the debilitating impacts of global warming such as heat waves, droughts, floods, hurricanes, and biodiversity loss. The industry has a significant role of supplying the critical minerals and metals required for the energy transition. Yet, it is faced with numerous risks which may hinder the uninterrupted supply of essential materials for the transition. This study leverages resilience theory and borrows insights from risk management literature to build a framework of mining industry supply chain resilience to help mining firms and emerging markets nations to seamlessly deliver critical raw materials. In this critical review of literature, we substantiate and expand on the four dimensions of risk categorised as machine and systems factors, human factors, general factors, and environmental factors, which must be addressed in building critical minerals and metals supply chain resilience. It is found that building supply resilience calls for developing strong risk assessment and management capabilities to moderate how the four dimensions of risk relate with supply chain resilience. The findings have significant practical implications for mining industry's ability to seamlessly maintain the supply of critical minerals from emerging markets, and for building theory of critical minerals and metals supply resilience.

1. Introduction

Minerals and metals supply chains have been disrupted with increasing frequency and intensity in recent years. The disruptions have included natural disasters and crises such as wars, earthquakes, climate change triggered crises such as wildfires, floods, and heat waves. More recently, supply chains were disrupted by a global pandemic, that is the COVID 19 novel virus which brought the whole world to a standstill (Kumar et al., 2023; Cantelmi et al., 2022) and the European war between Russia and Ukraine, with several other countries taking a direct or an indirect part (Esfandabadi, Ranjbari and Scagnelli, 2022). On an ecological front climate change induced disasters such as cyclones, hurricanes, heat waves, floods and several others have resulted in disruptions requiring emergency interventions (Qin et al., 2023). As the emergency management field is interdisciplinary, drawing upon bodies of knowledge in the physical and social sciences, we find it useful to shade light to our conceptualisation of resilience in the context of future minerals and metals supply. An emerging stream of literature suggests that a disaster resilient supply chain learns from its experience, supports sustainable development policies, mobilizes the government, and demands that effective policies be implemented (Mousavi and Bossink, 2017). The body of literature builds on established stages of emergency management, including hazard mitigation, disaster preparedness (readiness), emergency response, and disaster recovery in the face of disruptions.

When such disruptions are experienced, supply chains may withstand them, but if they are not adequately prepared, they may collapse with often costly consequences (Ellis, 2022). The capacity of supply chains to revert to their original state or to a better position after a disruption has been defined as supply chain resilience (Chu et al., 2020). Although the concept of supply chain resilience has been discussed for some time now there is still lack of consensus on the meaning and dimensions of resilience.

This paper scopes the concept of supply chain resilience in the critical minerals and metals supply context. Minerals and metals are very important in advancing the global economy, as much as they are needed for the just energy transition (Islam et al., 2022). Specifically, critical minerals and metals are significant in producing energy transition

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materials such as batteries, energy storage and electric vehicle charging facilities, windmills, solar panels, and even hydrogen-based energy production. As such, there is undoubtedly rising global demand dynamics for these minerals and metals. The global market typically sources the minerals from areas where there are endowments, which has ultimately helped different economies shift to renewable energy resources and adopt electric vehicles (EVs) and rapid electrification processes (Magyar, 2021). Apparently, renewable technologies are generally more raw material-intensive than traditional energy, such that, for instance, a 1-MW solar power plant requires three times more copper than a conventional power plant, and there are several other minerals needed, including indium or tellurium, cadmium, and silver, to construct solar panels (Islam et al., 2022). Lithium, cobalt, and nickel are also essential for electric vehicles and power storage batteries (Calvo and Valero, 2022). It is always noted that most of these minerals are concentrated in some selected areas of the globe, typically remote, less developed jurisdictions which makes the mineral-based clean energy transition process more intricate (Blengini et al., 2020; Palacios et al., 2018). Important minerals and metals for the energy transition have often been labelled critical materials because of the risks associated with their supply. In other words, their supply is not guaranteed due to numerous risks.

It is in this vein that this paper explores the leading minerals and metals risks and strategies for mitigating these risks to ensure seamless supply of these important resources for global economic development and reversing the debilitating effects of global warming. The paper views supply chain risks associated with critical minerals and metals that are sourced from developing and emerging markets regardless of their destinations. They may be sourced in emerging markets for local consumption or exporting to more developed markets. We argue that strengthening supply chains right from the source is important because a supply chain is only as strong as its weakest link (Jażdżewska-Gutta and Borkowski, 2022). Although all parts of the supply chain are important, a closer look at risks associated with minerals and metals from emerging markets deserves attention because the bulk of critical materials are exploited from these typically remote less developed contexts where labour costs are regarded as low and where the cost of relocation of people is comparatively low (Hendrix, 2022). Further, scholars have highlighted the dynamics associated with post-independence developing countries. For example, it is observed that the post-independence Kazakhstan experienced an initial period of deep recession and hyperinflation, followed by a period of superior growth, and economic stability from 1995, which attracted significant global foreign direct investments in natural resources, such as oil (Bibi, 2023a). Although the current global energy focus in on renewables, lessons could be drawn from fossil fuel dynamics to inform understanding of critical minerals supply vulnerabilities. Such a favourable economic scenario has enabled the country to attract enormous resources from the rest of the world through the financial account. It is in this light that this paper recognises the potential increased inflows of investments in Emerging markets. The paper makes a significant contribution to emerging markets critical minerals supply chain research, by synthesising literature on the risks associated with sourcing critical minerals and metals from these markets (Moerenhout et al., 2023). Such research is important, as it helps emerging market nations and mining houses deal with the risks and opportunities associated with over-relying on extraction of critical minerals, especially in the era of price and supply volatility associated with growing need for environmental and social sustainability (Bibi, 2023). Emerging market mining companies, including transnational mining houses have been criticised for human rights violations and environmental degradation, as they take advantage of Global South weak institutions (Ullah et al., 2021). There is need for deeper understanding of the risks resulting from geopolitical multiple tensions and interests on emerging markets resources between the superpower countries (Bibi, 2023a; Bibi, 2023b). This further highlights the limits that Global South economies face when their growth relies excessively on external financing which underscores the reason why further scholarly work in that direction is paramount (Bibi and Valdecantos, 2023 a).

Although countries and mining houses tend to flourish at the back of resources extraction and export, in the event of downturns the risk of perpetual decline and an end to such flourishing must not be ruled out, in view of recent strong social protests, and the current geopolitical tensions witnessed around the globe (Bibi, 2023 b; Bibi and Valdecantos, 2023 b).

By looking at both the opportunities created by building resilience capacity and the downside of lack of capacity in the face of disruptions, the paper proposes a framework for resilient critical minerals and metals sourcing from emerging markets and characterises the diverse risks associated with such exploits.

The paper aims to answer the following questions.

1) What are the leading minerals and metals industry supply risks faced in the 21st century?
2) How and under what conditions could these risks be mitigated to build supply resilience?
3) Why is building metals and minerals supply chain resilience important?

The paper is structured as follows: it started with an introduction section which is focused on the challenges facing the minerals and metals industry in the 21st century, showing how the industry finds itself faced with numerous risks ranging from natural disasters to geopolitical supply disruptions. The section is followed by the review methodology, a brief description of how the review was achieved. Section three looked at the supply chain resilience, while section four focused on minerals and metals supply risks, considering the various dimensions of risks. In section five we review the mechanics of risk mitigation for the critical minerals and metals mining industry and their potential to deliver supply chain resilience, and the costs associated with poor capacity for managing these risks. The subsequent sections attempt to build a minerals and metals supply resilience framework for sustainable resources supply in the face of growing disruptions. The final section looked at the future research directions and conclusions. Now that the introduction to the paper has been spelt out, we look at the methods used in writing this paper.

2. Review methods

This paper is divided into seven sections to provide a systematic literature review of the risks associated with minerals and metals supply, and the capabilities necessary for mitigating the risks to achieve supply resilience when sourcing materials from the Global South. The paper utilised an extensive review of literature based on key terms including supply chain resilience, critical minerals and metals, climate change, energy transition, minerals and metals supply risks, risk mitigation capabilities, resilience theory, and emerging markets minerals and metals. A keyword search was conducted by both authors simultaneously. The keywords were searched for in the title first, followed by the abstract before searching in the entire document. From the obtained sources, only literature with potential to answer the research questions were considered. The criteria for inclusion were potential to answer research questions, compatibility of utilised theoretical perspectives, extractive industries focus and recency. Therefore, we excluded literature that is dated or that follow conflicting theoretical perspectives as our study adopted a systems theoretical lens. After the first round of literature search, we grouped together the literature with the most citation frequency. This process was followed by search for sources that were cited in our literature list and those that cited sources in our generated literature list (Chipangamate and Nwaila, 2023).

Once a significant body of literature was generated, as demonstrated by saturation, a thorough content analysis was performed towards building a theory of critical minerals and metals supply resilience. This started with building categories from formulated codes and building themes from those categories. Together, the content analysis culminated in the development of a framework for critical minerals supply chain resilience.

3. Supply chain resilience

The mining industry supply chain is complex and resilience in this context represents a multidimensional phenomenon. What makes it more difficult to understand such a phenomenon is that supply chain resilience is a relatively new concept within a broader supply chain risk management research stream. Therefore, we allocate space for clarifying our understanding and conceptualisation of key concepts. Despite considerable research since the 2000s, fundamentally, there is still confusion and lack of consensus over the definition of Supply Chain Resilience (SCRES) (Spiegler et al., 2012; Mensah and Merkuryev, 2014; Tukamuhabwa et al., 2015). For example, Jiang et al. (2023) defined supply chain resilience in the mineral resources industry as "the ability of the downstream industry to recover its original state when the upstream suppliers face emergencies in the mineral resources industry". Although this definition captures the essence of supply chain resilience, it is problematic for the industry because of several reasons: by distincting between upstream and downstream, the definition fails to conceptualize a supply chain as a single network. Due to that misconception resilience is viewed, in this definition, as the ability of 'downstream industry to recover', undervaluing the need for the disrupted upstream industries to recover and transform as well (Roberta Pereira, Christopher, & Lago Da Silva, 2014). Table 1 chronicles how the definition of resilience in the context of supply chains has evolved since the early 2000s.

The theorisation of supply chain resilience is still embryonic for which a multidisciplinary perspective is useful. Building on the work of these scholars, we define supply chain resilience as the adaptive capability of the supply chain to prepare for unexpected events, respond to disruptions, recover from them by maintaining continuity of operations at the desired level of connectedness and control over structure and function, and transform in preparation for unplanned future disruptions efficiently and effectively. The definition is more comprehensive as it captures the facets of the resilience triangle (Bruneau and Reinhorn, 2006; Cimellaro et al., 2010; Eren Tokgoz and Gheorghe, 2014; Tokgoz et al., 2017) which considers factors such as the performance level, loss estimation and recovery time, and extend in this paper by adding the transformation dimension.

In defining supply chain resilience this way, we take a metaphoric view of the supply chain. Resilience is used in supply chain management as a metaphor, borrowing from natural sciences such as mathematics and physics, from which it was brought to several other disciplines (Spiegler et al., 2012). For example, adaptive capability is a well noted critical component of resilient ecosystems. The ideas of respond, recover, and retaining control and structure after disruption is characteristic across all the perspectives examining resilience including natural sciences (Hosseini et al., 2016), socio-ecological (Turner, Devisscher, Chabaneix, Woroniecki, Messier & Seddon, 2022), psychological, economics, organizational Ivanov and Dolgui, 2020), and emergency management (Barroso et al., 2011;Cantelmi et al., 2022). We argue that a metaphoric perspective to supply chain resilience conceptualisation is appropriate because the concept of supply chain is also a metaphor. A chain is originally conceptualised as a series of interconnected metal rings. Viewing business systems as a chain, therefore, qualifies the use of supply chain concept as a metaphor. However, the metaphoric usage of resilience has resulted in scholars taking a literal translation viewing resilience as nothing more than returning to original condition (Ponis and Koronis, 2012). We argue for resilient critical minerals and metals supply chains that are adaptive and transformational (Wieland and Durach, 2021) so that they are not static but dynamic, because minerals and metals supply chains are not only faced with engineering risks

Table 1
Definitions, changing focus and sources of supply chain resilience from 2003 to 2023.

Definitions	Additional Focus Areas to Definitions	Sources
Resilience in the supply network environment is the ability to react to unexpected disruption and restore normal supply network operations	Ability, supply network, react, disruption and restore.	Rice and Caniato (2003)
Resilience is the ability of a system to return to its original (or desired) state after being disturbed	Return to original state.	Christopher and Rutherford (2004)
The supply chain's ability to withstand and recover from an incident. A resilient supply chain is proactive – anticipating and establishing planned steps to prevent and respond to incidents. Such supply chains quickly rebuild or re-establish alternative means of operations when the subject of an incident.	Withstand, proactive, prevent, rebuild and re-establish.	Closs and McGarrell (2004)
Resilience in terms of the corporate world is the ability of the company to bounce back from a large disruption including the speed with which it returns to a normal level of performance.	Speed.	Sheffi and Rice (2005)
SCRES is not only the ability to maintain control over performance variability in the face of disturbance but also a property of being adaptive and capable of sustained response to sudden and significant shifts in the environment in the form of uncertain demands.	Adaptive, sustained response and demands.	Datta (2007)
Resilience of the supply network is the ability of the production-distribution system to meet each customer demand for each product on time and to quantity.	Production-distribution system, time and quantity.	(Priya Datta et al., 2007)
SCRES is the ability of a supply chain to maintain, resume and restore operations after a disruption.	Maintain	Gaonkar and Viswanadham (2007)
SCRES is the ability of a supply chain to reduce the probabilities of a disruption, to reduce the consequences of those disruptions when they occur and to reduce the time to recover normal performance.	Reduce probabilities of disruption and reduce consequences.	(Falasca et al., 2008)
The supply chain's ability to react to the negative effects caused by disturbances that occur at a given moment to maintain the supply chain's objectives	Negative effects and supply chain's objectives.	Barroso et al. (2010)
The system's ability to return to its original state or to a new more desirable one after experiencing a disturbance and avoiding occurrence of failure modes.	New more desirable and avoid occurrence of failure modes.	Carvalho et al. (2011a,b)

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Table 1 (*continued*)

Definitions	Additional Focus Areas to Definitions	Sources
The ability of the supply chain to cope with unexpected disturbances.	Cope.	Carvalho et al. (2012)
SCRES is the supply chain's ability to return to the original or ideal status after external disruption and includes both the abilities of adaptability to the environment and recovery from the disruption.	Adaptability and recovery.	(Xiao et al., 2012)
SCRES is the ability to proactively plan and design the supply chain network for anticipating unexpected disruptive (negative events), respond adaptively to disruptions while maintaining control over structure and function and transcending to a post robust state of operations, if possible, a more favourable one than that prior to the event, thus gaining a competitive advantage.	Plan and design, competitive advantage and maintaining control over structure and function.	Ponis and Koronis (2012)
SCRES is the adaptive capability of a firm's supply chain to prepare for unexpected events, respond to disruptions, and recover from them in a timely manner by maintaining continuity of operations at the desired level of connectedness and control over structure and function.	Continuity and connectedness.	Ponomarov (2012)
The ability of a system to return to its original state, within an acceptable period, after being disturbed.	Acceptable period.	Brandon-Jones et al. (2014)
The adaptive capability of a supply chain to prepare for and/or respond to disruptions, to make a timely and cost-effective recovery, and therefore progress to a post-disruption state of operations – ideally, a better state than prior to the disruption.	Preparation and growth.	Tukamuhabwa et al. (2015)
The adaptive capability of a supply chain to reduce the probability of facing sudden disturbances, resist the spread of disturbances by maintaining control over structures and functions, and recover and respond by immediate and effective reactive plans to transcend the disturbance and restore the supply chain to a robust state of operations.	Adaptive capability, reduce the probability and resist the spread.	(Kamalahmadi and Parast, 2016)
The capacity for an enterprise to survive, adapt, and grow in the face of turbulent change.	Survive, adapt and grow.	Pettit et al. (2019)
Supply chain resilience is the capacity of a supply chain to persist, adapt, or transform in the face of change.	Transform.	Wieland and Durach (2021)
The supply chain resilience of the mineral resources industry refers to the ability of the downstream industry to recover its original state when the upstream suppliers face emergencies in the mineral resources industry.	Downstream industry, upstream suppliers and emergencies.	(Liu, Lui and Zhang, 2023)

Source: Authors'work

(Hosseini et al., 2016) but socio-ecological risks (Turner et al., 2022), and natural disasters (Cantelmi et al., 2022), which are hard to predict.

Adaptability is an important quality for supply chains because after disruptions the envisioned state is usually different from the original one. Scholars have used diverse concepts such as flexibility and agility to illuminate the need to change, and sometimes very quickly (e.g., Christopher and Lee, 2004). From a theoretical perspective, evidence suggests that three theoretical perspectives have been leading in past research, and these are the resource-based view theory (RBV), dynamic capabilities theory and systems theory (Tukamuhabwa et al., 2015). Structural scholars have used resource-based view thinking to explain risks faced by the mining industry and for the extractivist countries that rely on them. For example, Bibi (2023 c) serves as a good base to understand such type of risk reporting the analysis done by the Economic Commission for Latin America and the Caribbean (ECLAC). It is argued that theories focused on competitive advantage alone are questionable, underlining how economies are currently set up to reproduce and deepen inequalities and environmental harm (Bibi, 2023c). Prebisch and the structuralist scholars suggested that because of the long-run declining terms of trade that minerals and natural resources are subject to, the industry (and the countries relying on them) could face strong economic structural difficulties, thereby posing risks that compromise critical minerals sustainability (Bibi, 2023).

Thus, although the resource-based theory has attracted a lot of attention in supply chain research, followed by its variant, dynamic capabilities theory, the two have been criticised for several other reasons. Notably, the theories are premised on the assumptions that a firm's competitive advantage emanates from resources that are housed in a specific organisation and the resources should be valuable, inimitable, rare, and non-substitutable (Barney 1991). However, firms with such resources are rare in practice, and in addition to that the theory explains a single firm with competitive advantage, without addressing how the rest of the organisations perform in the industry (Do et al., 2022). Evidence is increasingly suggesting that cooperation, rather than competition could be a source of increased benefits, especially in the mining industry where the demand far outstrips production capacity. An example of this need for collaboration is the emerging surging demand for critical minerals while firms become more embedded in ecology, society, and governance (Bhandari et al., 2022). Under these circumstances, we argue that systems theory (Ghadge et al., 2022) is more applicable as anchorage to understand the minerals and metals industry risks and their supply chain resilience. We draw from other studies that have utilised systems thinking to address research questions as diverse as exploring food supply chain disruptions during the Ukraine-Russia crisis (Esfandabadi, Ranjbari & Scagnelli, 2022) to the gleaning of the role of artificial intelligence in supply chain management (Sharma, Shishodia, Gunasekaran, Min & Munim, 2022).

However, despite criticism directed at the theory, we borrow insights from dynamic capabilities thinking to illuminate the flexibility demanded by resilient supply chains. While 'ordinary' capabilities (OCs) refer to the mining enterprises doing things right, dynamic capabilities (DCs) are linked with doing the right things at the right time which is important for critical minerals and metals supply resilience (Pitelis et al., 2023). Considering the importance of minerals and metals supply chains for different industries such as automobile, aerospace, energy transition, biotechnology, and others (Nwaila, Frimmel, Zhang, Bourdeau, Tolmay, Duuheim & Ghorban, 2022) the dynamic nature of adaptive capabilities allows the minerals supply chain to recover from disruptions, returning to its original state, or even achieving a more desirable state of future supply chain operations timely. Further, resilient supply chain includes important elements such as supply base strategy, collaborative planning, visibility, and factoring risk considerations into decisions (Wang and Zhao, 2023). Thus, there is a close linkage between the mining industry risk decisions and the future minerals and metals supply resilience.

A more nuanced understanding of these linkages is quite significant because extant related research to this point has largely dealt with defining the concept of supply chain resilience (Liu, Lui and Zhang, 2023), and identifying characteristics and components of resilient supply chains (Ponis and Koronis, 2012), leaving a surprising gap by failing to conceptualize the complexity of cause-effect relationships between some related constructs (Kumar et al., 2023). Despite the growing importance of minerals and metals supply chains and considering the accelerated energy transition, for example, very little research has been conducted to illuminate opportunities for fostering supply chain resilience in this important industry which makes this study an important step in that direction.

4. Minerals and metals supply chain risks

In recent years, we have witnessed a growing interest in the mining industry in issues related to risk assessment and management as supported by a significant number of publications and reports devoted to these problems. Surprisingly, there is paucity of theoretical and application studies that broadly focus on the diverse risks facing the mining industry (Shiquan and Deyi, 2023). Practitioners have been leading discussions on broad risk issues as shown by Ernest and Young, and KPMG's annual publication of mining industry risks (EY, 2023; KPMG, 2023). In this paper we answer rising calls for risk in mining to be analyzed not only in the human factor aspect, but also in strategic environmental impact and operational factors (Tubis et al., 2020), thereby closing an existing gap in research on systematic literature reviews and surveys of studies that would focus on these identified risk aspects simultaneously (Calzada Olvera, 2022a).

Supply chain risk emerged as a new risk in the Ernest and Young (2022) mining industry risks even though it is an issue that has been around the sector for some time. Different methods are used to analyse supply chain risks, including the world governance index (WGI), the Findahl-Hirschman Index (FHI) and the network analysis method (NAM) (Van den Brink et al., 2020; Habib et al., 2016). Several authors have alluded to other risks that indirectly contribute to supply chain disruptions, and they include political supply risks (Grover and Dresner, 2022) and social and legal risks that may accompany environmental damage (Mills, 2022). For example, countries with robust environmental regulations may halt some mining operations if the mineral being mined or the processes used to mine and or process are hazardous. This was substantiated by Chu et al. (2020) who also confirmed environmental risk as a threat to supply chains performance. Other supply chain risks include process and control risk, demand risk and sustainability risk (Colicchia et al., 2010; Corbett et al., 1999). Chu et al. (2020) further suggested the need to categorise these risks to have a better understanding of supply chain risks which is precisely what the current paper aims to achieve.

Ghadge et al. (2012) categorise supply chain risks as organizational risks (inventory risks), network risks (internal interactions) and environmental risks (natural disasters). Focusing on minerals supply chains, Zeng et al. (2021) lists some of the supply chain risks as unpredictable mineral prices, pricing, uncertain mineral resources, changeable market, supply disruptions and unstable geological conditions. Meyer et al. (2021) added some of the supply chain risks as a rise in prices, countless fluctuation in the demand of goods and unpredicted supply shortages. Similarly, Tang and Musa (2011) identified shorter product life cycle and an increasing demand as some of the complications of supply chains, specially, because they affect the operational performance through hamstrung transportation lead time and the need for costly supply-side product monitoring systems. According to Habib et al. (2016) supply risk can also be assessed through the geological and geopolitical supply risk as they relate to a particular resource. This paper attempts to understand how the industry could build resilience to deal with these risks for sustainable future supply of critical minerals and metals.

Leveraging the categorisation of risks advanced by Tubis et al. (2020) as a point of departure, this paper builds a theoretical framework for the mining industry to develop risk capabilities for supply chain resilience. Following an extensive literature review, Tubis et al. (2020) identified four dimensions of risk relevant to the mining industry: human factor, machines, environment, and general. Human factor refers to the risks that are associated with social issues in mining territories, such as social risks related to social licence to operate, and health and safety that may be affected by mining activities. At this stage, it is important to point out that risks could impact the mining operation or that risks to society may be caused by mining as a business. Both aspects of risk can impact production negatively, thus needing particular attention. Under the machines and systems factors dimension, the authors spoke about maintenance, accident/safety, and reliability. These issues may have significant implications on the operational performance of the mining industry, especially in the face of rapid technological shifts (Jiskani et al., 2022). The fourth thematic group is the environment, where some important sublevels were identified, including dual directional impacts of the environment on mining and the impact of mining on the environment (Bini et al., 2018). Now that the four dimensions are defined, next we delve deeper on the risks under each dimension in the following sections.

5. Machines and systems factors

Modern mines continue to deepen and as they deepen operating conditions are getting more difficult as costs of production also rise due to, for example, increased energy usage (Nwaila et al., 2022). To remain competive mines are resorting to modernising of their operations, paying attention to mechanisation, digitisation and automation (Chipangamate et al., 2023). As a result, the risk associated with failure of any of these technological factors could be problematic (Jiskani et al., 2022). Such failures could be related to machine breakdown, accidents or cybersecurity breaches (Pandey et al., 2020).

5.1. Digital innovation

The digital innovation risk is another risk that the mining industry is grappling with and demands that mining companies build more capabilities to deal with the threats. New technologies, systems and process upgrades, and autonomous trucks have made it easier for companies to operate and enhance performance, but more work still needs to be done to mitigate risks related to these developments (Mitchell, 2023). The mining industry is infamous for being slow to adopting change (Nwaila et al., 2022; Chipangamate et al., 2023), yet, digital transformation such as artificial intelligence, big data, cloud and others technologies are gradually modernising mining operations (Chipangamate et al., 2023). Although there are several opportunities for innovation, the risks of this new wave of digital innovation are equally high (Abdellah et al., 2022). Some of the challenges faced by the industry with a bearing on digital innovation risk include lack of understanding of digitisation, cyber security, inability to reach a strategy consensus, a haphazard digital transformation, customised software solution, lack of a workforce with the right skillset, inadequate scalability planning, incompetent suppliers and partners, complexity associated with mapping return on investment, and difficulties with intergating legacy infrastructure (Abdellah et al., 2022). The industry is dealing with technological lock-in (Chipangamate and Nwaila, 2023), risk aversion, having conservative attitudes, lack of support in key research areas which are important aspects of innovation (Calzada Olvera, 2022b). In addition to these mounting challenges, there is also the burden of raising significant investment capital, which exposes organisations to the risk of failure, especially considering the low risk appetite of the mining industry (Nwaila et al., 2022). Sánchez and Hartlieb (2020) highlight the divorce of digital transformation (DT) from information technology (IT) in some organisations as a core risk to the success of innovation because the two concepts must be carried out as a joint task throughout the organisation. However, it is important to remmember that with the increasing appetite for digital innovation comes the high risk of cybersecurity (Pandey et al., 2020; Gaber et al., 2021).

6. Human factors

6.1. Social licence to operate

The social licence to operate (SLO) concept has been widely used in mining studies and practice to refer to the generalised acceptance of a mining operation and it's activities by local communities and other stakeholders (Moffat and Zhang, 2014). To remain operational organisations ought to be committed to furthering the establishment of trust and building solid relationships with their communities and other stakeholders (Chipangamate et al., 2023). This can be achieved when mining companies contribute to the lives of their host communities and to protection of loval cultural heritage (MacPhail et al., 2023). This view is further supported by Nelsen and Scoble (2006) who confirm the role of SLO in mine planning, license renewals and new mining developments. Collins and Kumral (2021) identify the detriment of having a gap between organisations and communities in cases where having a social license to operate (SLO) is not prioritised.

The social license concept took centre stage in the mining industry from the late 1990s, yet it has spread to other key industries like energy, forestry, construction and agriculture. However, it is still more prevalent in the extractive industries as the environment and the people who live in it are greatly affected by mining, and therefore the importance of these industries gaining legitimacy (Demuijnck and Fasterling, 2016). Because mining operations may not proceed without the tacit acceptance of host communities, the social licence has emerged as a leading risk for the mining sector (EY, 2023; KPMG, 2023; MacPhail et al., 2023). Scholars have argued that work stoppages associated with community conflicts could lead to significant financial losses and supply chain disruptions, as witnessed in Peru and other developing economies on a more frequent basis (Triscritti, 2013; Paredes, 2022). In Africa, the SLO idea is even more important because as many as 25% of mining companies are facing community conflicts, posing significant critical minerals supply risks (Bezzola, Günther, Brugger & Lefoll, 2022).

6.2. Workforce

The mining industry, like several other sectors is facing an exodus of experienced talent due to resignations and retirements where getting replacement from younger potential employees is hard (Kilu et al., 2021). Mining companies are then prompted to spend money upskilling and reskilling workers. Mining costs are increasing due to increased inflation rates, and costs of employees whilst there is no significant increase in productivity. The industry is faced with the challenge of attracting young generation of employees while ensuring that the ageing workforce imparts skills to the new generation (Mok et al., 2023). Diversity and inclusivity is, therefore, suggested as a way to deal with the workforce risk as the mining workforce is rapidly ageing globally (Kilu et al., 2021).

6.3. Health and safety

Health and safety are very serious risks as underground and open cast mines become deeper and productivity keep declining due to lower ore grades (Nwaila et al., 2022). Kunda et al. (2013) studied the underground mine workers in Zambia and concluded that despite the many safety interventions, automation, increased attention and stringent regulations within the sector the industry is still one of the most dangerous industries to work in. The researchers further argue that there is more risk in underground mining than in surface mining as underground mining involves drilling, blasting and other labour-intensive tasks under the weight of rocks above. Studies conducted in the South African gold mines concluded that tuberculosis (TB) incident rates were higher in South African gold mines than elsewhere in the world (Chihota et al., 2022). These statistics were further confirmed by van Halsema et al. (2012) in their study on gold mining workforce in South Africa between the years 2002–2008 where TB was noted to be among the highest health risks in gold miners. Additionally, more risks directly impacting productivity were hypertension and other non-communicable diseases (Mawaw et al., 2019; Lala et al., 2016). As a result, miners conduct annual medical examination where they get routinely screened for mycobacterial diseases amongst other tests to try and manage risks. In addition to the health risks on mine workers, surrounding communities have been reportedly exposed to health and safety risks emanating from noise, gasses and dust from mining operations. Although these risks affect the workforce and communities, it is important to note that health problems also affects the mining industry through reduced productivity due to absenteesm of employees. The industry is further affected by the increased burden of community health provision which rises when communities are unwell. During the COVID-19 pandemic, it became clear that the health risks of communities have a direct bearing on the organisations as there was seamless disease transmission from communities to the mining companies and from mining workers to communities.

Health and safety risks have also been excerbated by the increasing frequency and intensity of tailing storage facilities failures. Some of the notable failures that have had significant health and safety impacts include the Fundao tailings dam failure in Brazil in 2015, where dangerous human and environmental exposure to metals was reported (Paulelli, Cesila, Devóz, de Oliveira, Ximenez, dos Reis Pedreira Filho and Barbosa Jr, 2022). In January 2019 there was yet another major tailings facilty collapse in Brazil, which is regarded as having had the worst devastating impacts on the people, economy and environment (Rotta et al., 2020). More recently, in September 2022 a dam holding liquid mine waste from a tailings reprocessing operation near Jagersfontein diamond mine in South Africa's Free State province collapsed, releasing a flood of mine slurry that swept away houses and cars, killed one person and injured several others, with far-reaching environmental impacts (Banya, 2022).

7. General factors

7.1. Geopolitics

Geopolitics in the form of global conflicts and trade tensions have become a major risk for the industry. This risk was made clearer through the war in Ukraine, which caused world politics to be impacted with multiplier effects on supply chains. Geopolitics is now a major potential risk factor within the natural resources sector as demand for these resources in the large economies (China and the United States of America) increases (Dogan et al., 2021), while supply risks may prevent sourcing from certain regions. The risk causes fluctuations in natural resources rents because of the dynamic nature of demand and supply (Afşar et al., 2022). For example, the September 2011 event in the United States of America is a geopolitical risk that let to oil industry instability (Habib, et al., 2016).

Geopolitics are macro-environmental factors which makes it difficult to manage as they are beyond the mining industry's control (Mitchell, 2023). China and several other countries are highly affected by geopolitics due to their high demand for imported critical raw minerals and being high renewable energy technology producing countries (Islam et al., 2023). Caldara and Iacoviello (2018) allude to the threat of terrorist attacks which can spike a war leading to global unrest. Rumokoy et al. (2023) highlight the detrimental effects of geopolitics which affect nations and industries resulting in a change in key markets, competition in economies and a rise in resource nationalism. Similarly, the detailed work of Bibi and Valdecantos (2023 a) highlights how recent tensions around the Russian-Ukrainian war impacted other (fossil fuel) natural resources industries and the magnitude of the impact of such tensions on natural resources supply chains.

7.2. New business models

New future-centric strategies to capture and share value need to be developed because of the demand for new commodities and the central role that sustainability is playing in business (Laukkanen and Tura, 2020). It is key that new value is created while reshaping current models in line with sustainability and creativity demanded of the 21st century mining industry (Chipangamate et al., 2023). This transition calls for new business models of creating shared value for the mining industry to contribute to the SDGs meaningfully. The reviewed papers, however, do not view business models as a risk or threat, instead they view them as an issue to be addressed by mining companies wanting to remain competitive (Bini, et al., 2018). We argue that static business models pose a significant risk to the mining industry, which has traditionally been known to be static and rigid regarding new ideas (Nwaila et al., 2022). Business models can be a major risk in a fast-paced, volatile, uncertain, complex, and ambiguous (VUCA) environment. For example, delivering value beyond compliance has become pertinent (Drusche and Krause, 2021). The current mining business model where benefits and profits accumulate only to shareholders and not the host communities where the negative impacts occur needs to be revised. The new business model should incorporate business delivery and social results if the industry is to achieve sustainability (Dunbar et al., 2020; Bibi, 2023 a; Bibi and Valdecantos, 2023 a).

7.3. Capital

The mining sector is capital-intensive because of the expensive equipment, structures and other required resources for operations (Frolova et al., 2019a, b). Ediriweera and Wiewiora (2021) emphasised how the lengthy period of explorations and other operational issues involve a large capital investment for mining operations. According to Frolova et al. (2019) some of the investment risks include inflation and exchange rates instability, mineral, raw material and labour markets swings, capital and equipment cost structures, government restrictions, regulations and legislation, economic and financial crises. Further, there are also foreign trade risks for organisations conducting trade activities abroad because of imposition of restrictions on the supply of goods in addition to political risks associated with adverse socio-political changes in a country (Frolova et al., 2019b).

Africa is regarded as a continent with a high risk of doing business due to poor institutional environment and political interference in business operations (Frynas and Buur, 2020). Furthermore, state participation in mines can be as high as 51%. In Botswana the government requires equity interest of about 15–25% in all new mining projects, board representation and other related tax deductions, whereas, in Chile, capital may only be repatriated after three years. In Zambia the government had equity of about 20% from 2008 to 2013 in the country's three largest mining companies (Lundstøl, 2022) (see Fig. 1).

Rumokoy et al. (2023) refer to the direct effects of geopolitics on firm investment decisions leading to declining profitability in mining companies in Australia. Caldara and Iacoviello (2018) further questioned the effects of geopolitics on firm investments within different industries. The energy demands are forcing companies to transform by responding through investing in other commodities that are future-centric, which include copper and lithium, whilst divesting coal assets. Together, these factors have the effect of chasing away capital from the mining sector into other alternatives, posing a serious risk (Nwaila et al., 2022). Fig. 2 shows the process used by mining firms in screening their investments for risk (see Fig. 3).

8. Environmental factors

Ecological factors are growing in popularity over the past few years. The dual ecological crises of climate change and biodiversity loss are emerging as a serious risk for the mining industry. On environment and climate change, issues like biodiversity and water stewardship urgently need attention. Together with social and governance issues, the role of what has famously become environment, social and governance (ESG) in the mining sector is becoming increasingly prominent given the fact that mining companies are now required to incorporate ESG principles within their operations and corporate strategy. Some companies use ESG to manage their reputation which adds value to the organisation by demonstrating commitment to sustainability for long-term financial performance (Asante-Appiah and Lambert, 2022). The rise to prominence of environmental risks is closely linked to other risks such as social licence to operate because negative environmental impacts erode stakeholder trust thereby diminishing social licence to operate (Moffat and Zhang, 2014).

Environmental impacts caused by mining like noise, dust, water pollution and depleting water tables due to pumping, adversely affect communities, especially in the era of climate change and global warming, where water and sometimes energy are closely related to the abundance of water for hydroelectricity generation. Scholars have noted the underground water depletion associated with lithium mining in the Lithium Triangle of Chile, Argentina, Bolivia in Latin America, and the African Lithium Triangle of Zimbabwe, Namibia, and Democratic Republic of Congo (Chipangamate and Nwaila, 2023; Moran et al., 2022), highlighting the potential risks of conflicts with local communities as the social licence to operate is eroded (Chipangamate and Nwaila, 2023). If not closely paid attention to, these risks may negatively impact the mining industry's success (Petavratzi et al., 2022). The rising calls for a reduction in carbon footprint are a huge risk for the industry because the calls for green transition have resulted in several countries pledging to achieve net zero emissions by 2050 (Van Coppenolle et al., 2023). Green transition requires much mining to extract the critical minerals and

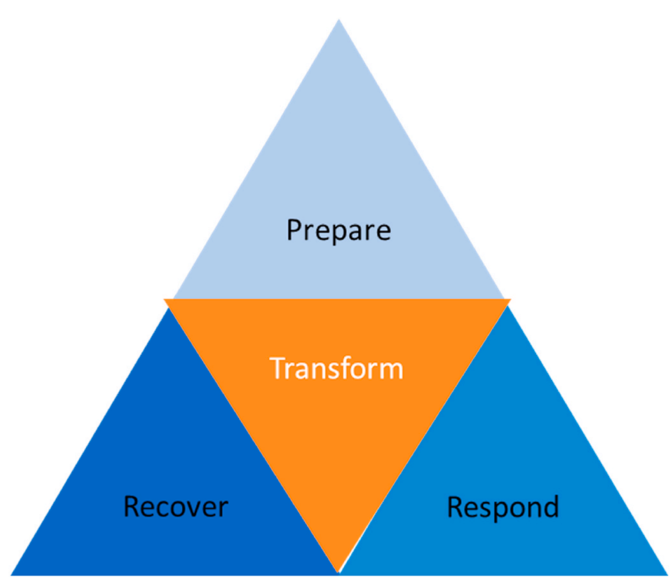

Fig. 1. The resilience triangle with an extended transformation dimension. Source: Authors' formulation

Fig. 2. Risk management process.
Source: Authors' formulation

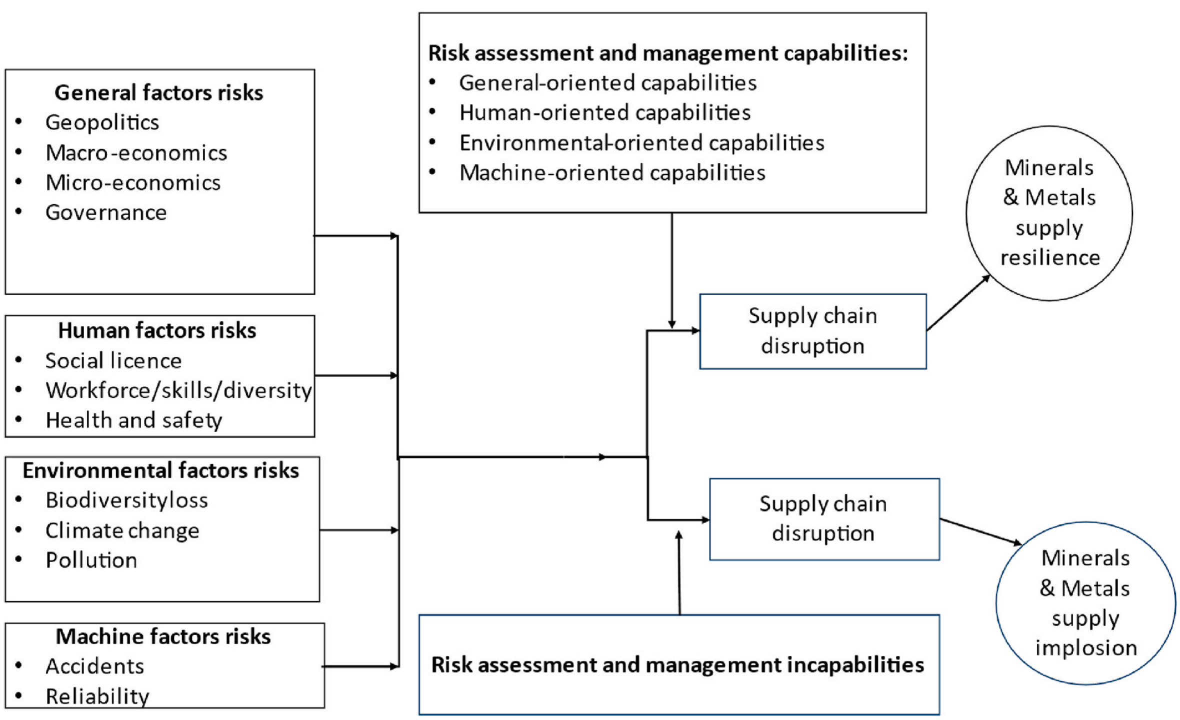

Fig. 3. Dynamic framework of building minerals and metals supply resilience.
Source: Authors' work

metals needed for the new energy alternatives, yet the mining industry is one of the highest emission generators (Cox et al., 2022). There are, however, fears that if not checked, the accelerated mining could increase the carbon footprint, or the focus on carbon footprint reduction may compromise mineral and metals extraction, which could be detrimental to the transition targets (Ahmed et al., 2020). All these factors affect mining sector operation (Maybee, 2023). Table 2 shows the diversity of risks and uncertainty.

Table 2
Diversity of risks and uncertainty.

RISK		UNCERTAINTY	
Tangible risk Known	Intangible risk Unknown	Tangible uncertainty Known-unknown	Intangible uncertainty Unknown
Risks include production rate variations, commodity price, exchange rate fluctuations, capital expenditure.	Risks include floods, underground collapse, supply and demand fluctuations.	Risks include climate change, nationalism, labour instability.	Risks include sanctions, war.

Source: Authors' work

8.1. Climate change in mining communities

The issue of climate change is a threat to the mining industry as it poses a huge risk to the sustainability of the industry. Bour et al. (2023) allude to the importance of the industry urgently paying attention to this risk which requires businesses to act with urgency and as a collective. South Africa is ranked in the top twenty of the most carbon–intensive global economy on emission per GDP basis. This is a big challenge for the country because there will be mounting pressure as other trade partners commit to low-carbon emissions whilst seven of the country's key trade partners commit to a net-zero target and these partners include, China, EU, UK, USA, Japan and South Korea (Bour et al., 2023). In South Africa, thermal coal is one of the most exported resources yet, the pressure to phase out the product globally is increasing as the world moves to cleaner energy technologies (Bour et al., 2023). Further, mining infrastructure like transport routes are prone to structural defects and failure due to extreme weather conditions caused by climate inconsistencies.

9. Dynamic risk assessment and management capabilities

Dynamic capabilities literature attempts to answer the question of how and why some firms manage to thrive in markets with rapidly changing technological, social, and market environments while others vanish (Leemann and Kanbach, 2022). For purposes of this study, dynamic capability refers to "the capacity of an organisation to purposefully create, extend or modify its resource base" (Helfat and Martin, 2015, p. 4). Drawing from this conceptualisation of dynamic capabilities, it is argued that, dealing with rapid changes such as those caused by mining industry risks requires building strong capabilities for assessing risks through the triad of sensing, seizing, and transforming (Leemann and Kanbach, 2022). Together, these capabilities allow mining industry firms to sense risks, and seize opportunities to capitalise on their resources for transforming systems and processes, thereby dealing with various risks caused by machine and systems, general, and environmental factors (Akbari-Kasgari et al., 2022). It is, therefore, argued that dynamic risk assessment and management capabilities enhance the mining firm's ability to deal with risks (Afşar et al., 2022), ensuring seamless supply of critical materials which is a key attribute of resilient supply chains.

By developing dynamic capabilities, the industry will overcome the litany of risks that threaten the smooth supply of critical materials. For example, mining companies can work towards enhancing energy efficiency, securing water resources to deal with environmental risks (Bini et al., 2018). By so doing they proactively work towards being early movers in addressing climate change by scanning the market and tracking risk indicators as basis for integrating the risks of climate change into critical assessments and planning of resource policies and other strategies directed to the sustainability of the industry. Mining companies can run scenarios and simulations to gauge different risk implications. They can develop renewable energy as alternatives by starting off with a hybrid grid supply (Gusc et al., 2022). In overcoming the risk posed by climate change, mining companies can intergrate the risks of climate change into critical assessments and planning of resource policies and other strategies directed to the sustainability of the indutry.

Similarly, Collins and Kumral (2021) suggest mining companies could building and maintaining social licence to operate to reduce risks in operations which can be caused by lack of approval from the local community or broader stakeholders. Working with foregin policy makers organisations can focus on governance gaps and argue for the setting of new standards. More emphasis is placed on collaboration among mining companies, regulators, scientists and other stakeholders in developing solutions to risks through adaptation strategies which can be integrated into existing mine operations (Pearce et al., 2011; Cai et al., 2014; Mousavi and Bossink, 2017; Neingo & Tholana, 2016). In managing some of the supply chain risks, companies can obtain required materials through sustainable schemes and sustainable mining initiatives (Van den Brink, et al., 2020).

To overcome ESG risks, Mitchell (2023) suggests that companies must intergrate ESG within their corporate strategies to show its importance. This could be done by utilising the capabilities of other service providers, such as auditors, to work closely with the company in evaluating their suppliers's non-financial performance and other financial-related activities (Asante-Appiah and Lambert, 2022; Garcia-Zavala et al., 2023). In a similar vein, and to reduce potential supply chain risks, Zeng et al. (2021) suggest that mining companies must have high stockpiles to overcome losses and understock prompted by uncertainties.

To demonstrate the flip side of building dynamic capabilities, this paper proposed supply chain implosion to suggest the sudden and violent collapse of a supply chain when faced with a disaster such as the risks caused by the COVID 19 virus (Cantelmi et al., 2022) and the Ukraine-Russia crises. Supply chains that lacked dynamic risk assessment and management capabilities collapsed (Orengo Serra and Sanchez-Jauregui, 2022), thereby compromising supply of critical materials (Durugbo and Al-Balushi, 2022). We refer to such chains as suffering from risk assessment and management incapabilities, building on the work of Yabe et al. (2022) who argue that weak supply chains suffer from inability to capture and withstand the effects of compounding and accumulating disaster shocks (Wernli et al., 2023). Similarly, scholars have attributed an incapability to manage risk as the primary reason for project budgets, timelines, and other goals being exceeded (Bahamid et al., 2022).

9.1. Towards a framework of future minerals and metals supply chain resilience

The review of the literature identified and broadened four (4) dimensions of risk, which are general factors, human factors, environmental factors, and machine and systems factors (Tubis et al. (2020). Using a systems perspective, we broadened these factors by integrating elements that are more applicable to the critical minerals and metals supply chains which originate in emerging markets. A key finding is that mining firms must invest in building dynamic risk assessment and management capabilities to achieve supply chain resilience (Leemann and Kanbach, 2022). Firms that do not invest in dynamic capabilities are bound to fail due to lack of risk assessment and management capabilities. We argue that this results in supply chain implosion (Escaith, 2010). An adaptive capability, which entails recovery, retaining control and structure, must be adopted to achieve supply chain resilience (Pitelis et al., 2023). If the supply chain can quickly recover from any breakdown without completely collapsing the structure and system, then that adaptability will help achieve supply chain resilience (Leemann and Kanbach, 2022).

Furthermore, other capabilities like dynamic capabilities coupled with non-substitutable and valuable resources help improve supply chain resilience because the rareness of their qualities will help them sustain a competitive advantage position in the market. Mining companies can take advantage of strong partnerships and collaborations with different stakeholders to build stronger resilience. If the supply chain is interrupted in any way, then the strength of alliances will be tested to avert a collapse of the system (Escaith, 2010). The dynamic capabilities theory alludes to the three (3) pillars of this theory: sensing, seizing and reconfiguration (Khan et al., 2021). The sensing pillar of this theory necessitates identifying any risk through the risk assessment process because as management senses the environment, they can identify a risk and quickly mitigate it. This is where management capabilities become crucial, as the ability to sense is the responsibility of management (Khan et al., 2021). The combination of all these capabilities brings about mitigating effects, including general-oriented, human-oriented, environmental, and machine-oriented capabilities to overcome supply chain challenges and achieve supply chain resilience.

The inverse of the above brings about supply chain implosion (Escaith, 2010). Suppose the company has not invested in identifying its capabilities and putting structures, processes, and systems in place to utilise them, the supply chain will be disrupted with costly outcomes. Moreover, if the role of management in identifying risk is not exploited, that will also lead to supply chain disruption and collapse.

10. Conclusions and future research directions

This paper aimed to propose a framework for building minerals and metals supply chain resilience in the face of growing risks. Through a systematic literature review, the paper finds that supply chain risks range from those resulting from general factors, such as geopolitics, macro, and micro-economics; human factors, such as licence to operate, workforce and skills shortages; environmental factors, like biodiversity loss, climate change and pollution; and machine or technology risks. To effectively deal with these risks, the paper finds that there is need for developing capacity in respect of the risk factors to deal with risks associated with general, human, environmental and machine factors.

Further, an important finding of the study is the cost of risk management incapability, which may lead to supply chain implosion, that is, a sudden and often violent collapse of the supply chain. Supply chain implosions may result in extended downtime or permanent collapse following disruptions to supply chains. The poor institutional context, such as poor governance, corruption, and underdeveloped legal frameworks may exacerbate the costs of incapability. There is, therefore, need to deliberately build risk management capacity so that supply chains stay resilient to withstand disruptions.

The literature review opened opportunities for future minerals and metals supply chain studies. It is recommended that future studies look at qualitative and quantitative research to test the outlined propositions as represented in the framework. The current study focused on minerals and metals supply from emerging markets, it could be useful also to understand how these risks differ or resemble developed markets risks and what capabilities would be needed to mitigate such risks in these contexts. It is expected that the risk factors and their effects may be affected by different institutional factors.

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CRediT authorship contribution statement

Nomkhosi Radebe: Conceptualization, Resources, Writing – original draft, Writing – review & editing. **Nelson Chipangamate:** Conceptualization, Formal analysis, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare no interest that may compromise the research findings.

Data availability

No data was used for the research described in the article.

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