Resources Policy 118 (2026) 105932

Contents lists available at ScienceDirect

Resources Policy

journal homepage: www.elsevier.com/locate/resourpol

A holistic methodological framework to support strategic procurement and supplier selection for sustainable supply chains of mineral resources within a changing global landscape

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ARTICLE INFO

Keywords:
Sustainable supply chain
Critical raw materials
Holistic risk assessment
Strategic decision-making
Geopolitical dynamics
Supplier selection

ABSTRACT

The procurement of raw materials has become increasingly complex and risky, driven by the expansion of emerging markets, technological advancements, and evolving geopolitical dynamics. The study introduces a holistic methodological framework designed to support decision-makers in assessing and comparing the multi-dimensional risks that influence the procurement of raw materials. The framework provides a structured, simulation-based approach that integrates economic, environmental, societal, political, and technical factors, enabling stakeholders to identify the most resilient sourcing strategies while optimizing procurement options. Methodologically, the research work leveraged on the Holistic Risk Analysis and Modelling (HoRAM) method, whose construct is in line with ISO 31000 for risk management. It offers a flexible approach capable of integrating both qualitative and quantitative factors, enabling a detailed and systemic understanding of supply chain risks, meant as uncertainties on objectives.

The aim of the study is to present a generalised previsional model capable of supporting the analysis of risks associated with the supply chain of raw materials, using the supply chain of Cadmium from the USA, Sweden, Peru, and Australia to Germany as a case. According to the calculations the USA shows a superior performance and comparable low expected risk costs. Sweden and Peru, follow with similar, but medium-risk pattern, while Australia shows the highest risk performance. The USA has also the highest resilience level regarding the analysed external factors, whereas Peru shows the lowest robustness.

1. Introduction

Modern technologies such as mobile phones, computers, automobiles, and renewable energy systems like solar and wind power, rely heavily on a wide range of metals, including rare earth elements (REEs) and indium (Blengini et al., 2017; Månberger, 2023; Riva Sanseverino and Luu, 2022; Torreggiani et al., 2021). While high performance and scalable production are essential for global deployment, the availability of raw materials required for these technologies is equally critical. Disruptions at any stage of the supply chain can delay or halt production processes (Wentker et al., 2019). For decades, the growing evolution of new technologies, the increasing diversification of metals needed for specific high-tech applications, and the rapid expansion of emerging markets (particularly China and India) have substantially altered global raw material supply dynamics (Ali et al., 2017). Consequently, industrialized nations have witnessed a significant deterioration in their raw material supply, raising concerns regarding long-term availability, price stability, and strategic dependency (Simon Glöser-Chahoud, 2017).

Mineral availability depends on a wide range of qualitative and quantitative factors such as accessibility, energy requirements, societal acceptance, environmental protection, governance standards, and technological maturity of extraction processes. Unlike manufactured goods, mineral resources are geographically constrained by the distribution of deposits in the Earth's crust, which limits sourcing flexibility

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https://doi.org/10.1016/j.resourpol.2026.105932
Received 6 November 2024; Received in revised form 16 April 2026; Accepted 20 April 2026
Available online 9 May 2026

and often leads to high levels of supplier concentration (Groves et al., 2025; Müller et al., 2025). This concentration is further reinforced by the high capital intensity required for exploration, mine development, and operation, which raises entry barriers and restricts participation to a limited number of firms and jurisdictions (Fung and Korinek J., 2013; Pietrobelli et al., 2024). In many cases, extraction activities are also subject to strong political influence, as mining companies are state-owned, state-backed, or operate under tightly regulated licensing and export regimes (Bechtum, 2024). As a result, ensuring continuity of supply and limiting disruptions becomes a primary concern in raw material procurement, frequently taking precedence over short-term cost optimisation or environmental performance alone (Hofmann et al., 2018). These challenges are further worsened by the fact that mineral extraction and early-stage processing often occur in regions characterised by heterogeneous institutional quality, regulatory capacity, and governance standards (Cole, 2023; Lèbre et al., 2019; Lee et al., 2020). In such contexts, Environmental, Social, and Governance (ESG) risks, traceability limitations, and political instability interact with technical and logistical factors, creating systemic vulnerabilities that propagate along the supply chain (Auld et al., 2018; Cole, 2023; Hofmann et al., 2018; Lèbre et al., 2019, 2020; Schöneich et al., 2023).

The combination of demand growth, geological constraints, concentration of suppliers, and uneven governance conditions makes raw material supply chains qualitatively different from other industrial supply chains. These factors influence production costs, operational feasibility, and the broader environmental and societal impacts of mining activities (Vidal et al., 2017; Zanoletti et al., 2021). For companies, the primary concerns include managing cost efficiencies, ensuring timely deliveries, and maintaining quality standards within fluctuating market demands and geopolitical uncertainties (Dong, 2022; Lv and Li, 2021; Otterbach and Fröhling, 2025). Governments, on the other hand, need to guarantee national security and economic stability by ensuring a steady supply of (critical) raw materials, which often involves negotiating complex international trade agreements and fostering strategic alliances (Crochet and Zhou, 2024; Xhaxhollari et al., 2016). Societal issues include the environmental and social impacts of mining and production activities, which can lead to ecological degradation and social disorder if not managed properly (Franken and Schütte, 2022; Khobragade, 2020; Singh, 2019). These challenges necessitate a comprehensive approach to supply chain management that not only addresses immediate operational concerns but also integrates long-term sustainability goals and risk mitigation strategies.

There is not a unified standard definition and interpretation of sustainability in the global supply chain (Ghorbani et al., 2021), but, at the same time, there is a growing pressure on firms to address ecological and social sustainability while securing their competitive position in the marketplace (Fahimnia et al., 2015; Foerstl et al., 2010; Mangla et al., 2015). Moreover, the increasing global demand for metals intensifies geopolitical conflicts, necessitating diversification of supply chains and strategic partnerships.

Recent geopolitical shocks and disruptions, such as the Covid-19 pandemic, the Russian-Ukrainian war or the energy crises in China, have further highlighted the vulnerability of global raw material supply chains. These events have reinforced the need for diversified sourcing strategies and robust risk assessment approaches capable of supporting long-term supply security. This pursuit should not solely focus on established partners; it should also prioritize enhancing cooperation with other nations to broaden the range of potential partners (Müller et al., 2023).

Thus, a question arises from the perspective of companies that rely on the import of natural resources: *which supplying countries should be strategically selected to reduce supply risks while maintaining cost efficiency?* Several studies are being published on this topic, and two distinct strands emerge that could help answer this question. One focuses on the criticality of raw materials, which evaluates their economic importance and the likelihood of supply disruptions. The conventional methods for assessing raw material criticality, like the criticality matrix used by the European Commission (Directorate-General for Internal Market Industry Entrepreneurship and SMEs, 2023; Ferro and Bonollo, 2019; Glöser et al., 2015), have their limitations. While they highlight materials of economic importance and high supply risks, they often fail to consider dynamic interdependencies between influencing factors and to accommodate future changes in the supply landscape. This approach is generally limited to a static, material-based perspective (Ioannidou et al., 2019; Knoeri et al., 2013). Even with the recent publication of the Critical Raw Materials Act (CRMA) (Directorate-General for Communication and European Commission, 2023) a clear strategy or methodology for supplier selection is still missing.

The other strand is more general and involves supply chain management, addressing broader issues of risk and resilience in supply networks. Existing approaches borrowed from supply chain management, such as Petri Nets (PNs) or Multi-Criteria Decision-Making (MCDM) assessments (Sari et al., 2018; Tuncel and Alpan, 2010; Wang et al., 2019), offer structured decision support but often struggle to represent uncertainty, dynamic interdependencies, and opportunity-related aspects of risk in line with ISO 31000 principles. This highlights the need for flexible, risk-oriented frameworks capable of capturing complex interactions across the entire supply chain (Christopher and Holweg, 2011; Reiner et al., 2014).

To the best knowledge of the authors, there are no existing studies in the literature that holistically account for the most relevant factors in the value chain of raw materials supply addressing the societal, technical, economic, political, and environmental dimensions. Therefore, a robust procurement management strategy characterized by holistic supply chain risk management is considered essential for addressing the complex challenges associated with raw material procurement (Putri et al., 2020).

This study introduces a logic-driven, simulation-based framework that enables the evaluation and comparison of alternative supply countries by explicitly modelling interactions among different risk factors. Rather than focusing solely on cost or performance indicators, the proposed approach adopts a systemic risk perspective, supporting supply diversification, resilience planning, and sustainability-oriented decision-making in a possibly changing global landscape. To operationalize this aim, the study adopts the Holistic Risk Analysis and Modelling (HoRAM) method, which is in line with ISO 31000 for risk management (Iso, 2018). This approach enables the integration of qualitative and quantitative risk factors into a unified decision-support framework. The proposed framework is intended to support strategic procurement and sourcing decisions in organizations that rely on imported mineral resources and operate under supply-security and sustainability constraints. In particular, it is designed for decision-making units within large downstream industrial actors and resource-dependent economies, where supplier selection involves balancing economic performance, geopolitical exposure, environmental and social considerations over long planning horizons.

In contrast to conventional approaches, the proposed framework does not reduce performance to a single composite index nor assume independent evaluation criteria. Instead, it models the logic-stochastic interdependencies among economic, environmental, geopolitical, technical, and societal variables, generating a universe of scenarios and associated risk distributions and spectra. This shift from static, weight-based evaluation to dynamic risk-structure modelling enables decision-makers to analyse how uncertainties propagate along the entire value chain and how external disturbances may reshape procurement decisions. In the context of mineral resource supply chains, characterised by geological constraints, supply concentration, and geopolitical volatility, this dynamic modelling offers a methodological extension that addresses limitations identified in conventional supplier selection models (Christopher and Holweg, 2011; Tang, 2006).

The manuscript is organized as follows: Chapter 2 provides an overview of current research activities in the field of raw materials supply chain and details the literature review that forms the foundation of this study. Chapter 3 introduces the HoRAM method and reaffirms the motivations that have led to this methodological choice. Chapter 4 presents the case study and the results obtained. Chapter 5 discusses the results in relation to existing literature, explores their implications for decision-making and highlights possible advantages and limitations of the proposed framework and future research directions. Finally, Chapter 6 draws the conclusions from the application of the HoRAM method for the risk assessment of the supply chain of raw materials,.

2. State of the art

Examining the literature, one can define two strands of research concerning the risks for raw materials procurement. The first strand focuses specifically on the criticality assessment of raw materials, while the second one addresses the broader issue of supply chain management problems.

2.1. Criticality assessment of raw materials

Traditional criticality assessments typically rely on matrix-based approaches, positioning materials along two axes: supply risk and economic importance, as shown in Fig. 1. The resulting criticality score, often expressed as the product of these two dimensions, allows the comparison among different raw materials (Achzet and Helbig, 2013; Diemer et al., 2018; Gemechu et al., 2016; Glöser et al., 2015; Helbig et al., 2016; Graedel et al., 2012; Graedel and Nuss, 2014). Although widely used, these matrices often combine heterogeneous indicators into two aggregated dimensions, reducing transparency in how results are derived (Diemer et al., 2018). Moreover, variations in axes determination, indicator selection, weighting, and aggregation procedures lead to significant disparities in criticality assessments across studies (Calvo et al., 2018; Diemer et al., 2018; Frenzel et al., 2017; Schrijvers et al., 2020).

Generally, existing assessments are static and describe the current supply situation without accounting for dynamic aspects or long-term trends (Cimprich et al., 2019; Glöser, 2012). A more dynamic approach to criticality assessments has been highlighted as essential already by Glöser and Faulstich (Glöser, 2012). Moreover,

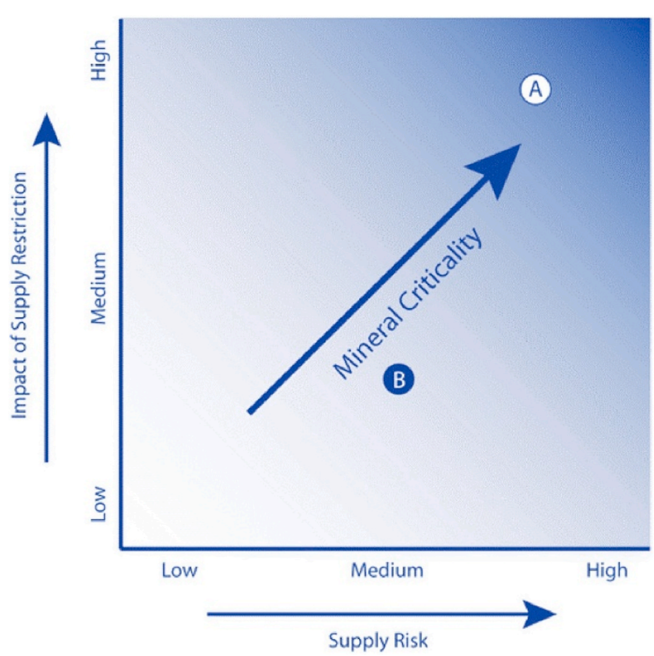

Fig. 1. Example of classical criticality assessment matrix, with a supply risk dimension and an importance dimension (Schrijvers et al., 2020).

environmental considerations in criticality studies have often been overlooked despite the substantial environmental implications of metals mining and manufacturing. This limits the ability of conventional approaches to capture changes in criticality over time and across the material life cycle (Knoeri et al., 2013). A further recurring issue concerns objectivity and transparency, as subjective choices related to aggregation and classification are not always clearly justified. This lack of methodological clarity impacts the interpretability and comparability of results, ultimately weakening confidence in the derived conclusions (Cimprich et al., 2019; Erdmann and Graedel, 2011; Schrijvers et al., 2020).

In response to these challenges, several approaches had been developed to enhance the efficacy of criticality assessments. Rosenau-Tornow et al. (2009) introduced indicator-based rankings aimed at capturing long-term supply and demand factors. However, the approach is data-driven and, given the limited accuracy of statistical datasets for mineral raw materials, the challenges the method tried to overcome still persist. Other approaches, such that proposed by Knoeri et al. (2013), integrate agent-based behaviour models with dynamic material flow models to assess the environmental risks associated with material substitution decisions. However, these approaches are based on significant modelling of uncertainty coming from the complexity reached with models' integration, extensive data requirements, and simplified assumptions necessary to manage and study complex systems. (Knoeri et al., 2013). Kim et al. (2019) adopted a fuzzy logic approach in their study to derive criticality assessments for selected minerals, offering a way to incorporate expert opinions and quantify criticality levels. They conclude that their approach still requires further consideration of the interpretation and methodological application. Santillán-Saldivar et al. (2021) address the recycling phase in criticality assessments using the GeoPolRisk method, but emphasize the need for further methodological development to better reflect the complexities of globalized supply chains. Gemechu et al. (2016) and Wentker et al. (2019) elaborated a method to integrate the assessment of the GeoPol-Risk into the Life Cycle Sustainability Assessment (LCSA) framework. To provide uncertainty analysis, they also coupled a Monte Carlo simulation. Yet, coupling different methods is always a critical step, as information can be lost, forgotten or misinterpreted (and then wrongly modelled). Moreover, performing an LCA requires a vast amount of data, and when it comes to the supply chain of raw materials, it can be challenging to collect the necessary data in terms of both quantity and quality (Schrijvers et al., 2020).

2.2. Risk assessment methods in supply chain management

Supply chain management (SCM) plays a crucial role in interconnecting suppliers, manufacturers, warehouses, and clients to ensure efficient production and distribution. In recent years, risk analysis and assessment methods have become an integral part of SCM research, aiming to identify, quantify, and mitigate disruptions that may affect supply continuity, cost efficiency, and sustainability (Sodhi et al., 2012). Different reviews highlight that supply-chain risk management evolved from purely operational models to systematic frameworks combining risk identification, analysis, evaluation, and treatment, as recommended by ISO 31000 (Fan and Stevenson, 2018; Kleindorfer and Saad, 2005; Rangel et al., 2015; Sodhi et al., 2012; Tang, 2006). These frameworks emphasize both the probabilistic nature of risks and the need to consider interdependencies across economic, environmental, and societal domains.

Numerous methods exist for SCM (Tuncel and Alpan, 2010), ranging from proactive risk management models, like that proposed by Pujawan et al. (Pujawan and Geraldin, 2009), to the use of Failure Modes and Effects Criticality Analysis (FMECA) coupled with Petri Nets (PN), as demonstrated by Tuncel et al. (Tuncel and Alpan, 2010). In their study, Tuncel et al. identify and assess supply chain risks through FMECA and integrate them into a high-level PN model to analyse how operational disruptions propagate through the network, expressing their effects in terms of delay and cost. Risk management is evaluated by comparing a reference scenario against predefined scenarios where mitigation actions reduce failure probabilities at an additional cost. While this approach supports operational performance evaluation under assumed conditions, it remains strongly case-specific and relies on fixed risk parameterisation, limiting its ability to capture systemic uncertainty, evolving conditions, and complex interdependencies characteristic of real-world supply chains.

Motivated by the limitations of deterministic methods in considering parameter changes, Manotas-Duque et al. (Diego Fernando et al., 2018) propose a financial assessment model for raw material supply decisions. This model, based on Present Value (PV) of cost, incorporates Monte Carlo simulation to analyse the effects of different independent variables on PV cash flow. However, they do not account for exogenous factors that could significantly influence the system and alter the results.

Other quantitative and hybrid approaches have been developed to improve the representation of uncertainty in supply networks. For instance, Fattahi et al. (2020) propose a two-stage stochastic program for supply chain network design that incorporates a new resilience metric defined as the expected increase in operational costs during recovery after a disruption. Their model optimizes location, capacity, inventory, and allocation decisions under normal and disrupted conditions, capturing resilience through recovery time and performance loss. However, the approach remains purely cost-based and focuses on facility-level disruptions, without accounting for broader socio-economic, environmental, or political drivers of risk.

Beyond these optimisation approaches, a different stream of research conceptualises supply chains as complex adaptive systems and applies agent-based modelling (ABM) to analyse disruption propagation and adaptive supplier behaviour. For example, Zhao et al. (2019) develop an empirically grounded ABM to study cascading failures and adaptation mechanisms across multi-tier supply networks. Similarly, Lohmer et al. (2020) use ABM to evaluate how digital technologies and collaborative mechanisms affect resilience dynamics and ripple-effect propagation. While ABM provides valuable insights into network topology, adaptive behaviours, and disruption propagation, these models depend heavily on detailed firm-level behavioural rules, competition data, and extensive scenario sets. Therefore, they become difficult to apply when the aim is to compare risk factors across multiple socio-economic, environmental, political, and technical dimensions, rather than model firm-level adaptation.

Bayesian Networks (BNs) have also been applied to model disruption propagation and causal dependencies in supply networks (Garvey et al., 2015). While BNs provide a powerful probabilistic framework, their application in supply-chain risk analysis is often limited by the need for detailed structural knowledge, large datasets to populate conditional probability tables, and the rapid growth in computational complexity as network size increases. Moreover, BNs typically represent risks at a single operational level, making it difficult to integrate broader socio-economic, geopolitical, and environmental dimensions.

While the methods discussed above primarily address disruption propagation and system-level resilience, another central stream of SCM research concerns the strategic selection of suppliers. This decision-making process is often addressed through multi-criteria decision-making (MCDM) assessments (Jasiński et al., 2018; Moktadir et al., 2024; Odeyinka et al., 2022). The complexity increases when multiple groups of people and experts are involved in the attempt to increase objectivity and try to avoid subjective factors. Previous studies typically assumed equal weighting for each criterion cluster, overlooking the varying opportunities, costs, hazards and threats associated with the selection of a specific supplier (Wang et al., 2019). Despite the abundance of supplier selection models, many of them tend to focus solely on hazards, often overlooking the possible opportunities that buyers may benefit from when opting for a particular supplier (Lee, 2009). Furthermore, since the mid-twentieth century, organizations have recognised the importance of ecological thinking and sustainability in business. Consequently, it is imperative to include environmental considerations when assessing the risks associated with different suppliers (Mangla et al., 2015).

A representative example of the integration of sustainability and risk management is provided by Giannakis and Papadopoulos (2016), who applied the Failure Mode and Effects Analysis (FMEA) technique to assess sustainability-related risks across environmental, societal, and economic dimensions. However, the method remains static and data-dependent, offering limited insight into the causal interrelations among risk factors or their dynamic propagation along the supply chain.

2.3. *Research gaps and motivation of the study*

Despite the extensive literature on raw material criticality and supply chain risk assessment, several important research gaps remain. First, criticality assessments typically adopt static, material-centred perspectives that condense diverse indicators into simplified risk matrices. These approaches often rely on subjective aggregation procedures and rarely account for dynamic trends or long-term system behaviour. Second, while SCM risk models provide valuable insights, they address only partial aspects of the overall risk landscape. Deterministic approaches (e.g., FMECA + Petri Nets) struggle to incorporate external drivers and cross-domain interdependencies. Monte Carlo and stochastic optimisation models quantify uncertainty but remain primarily cost-focused and require well-defined statistical inputs, limiting their applicability when uncertainty is structural. Complex system approaches (e.g., agent-based modelling and Bayesian Networks) can simulate behavioural adaptation and causal dependencies, but they heavily depend on behavioural, interaction, or conditional probability data, which are difficult to obtain or validate for long-term, multi-domain risk assessment involving political, environmental, societal, and governance dimensions. Third, supplier-selection studies tend to emphasize performance metrics or individual risk categories, often assuming equal weighting of criteria and overlooking opportunities and long-term vulnerabilities.

Therefore, the literature reveals a lack of holistic and multi-dimensional risk-assessment frameworks that can integrate quantitative information with qualitative descriptors (e.g., governance conditions, societal acceptance, or geopolitical stability) that are increasingly recognised as relevant but difficult to measure, validate, and harmonise across studies. Such a framework should remain operational under conditions of data scarcity, imprecision, and deep uncertainty. This study addresses these gaps by adopting the HoRAM method, a logic-based, simulation-driven framework that enables a comprehensive evaluation of risks along the raw material supply chain. HoRAM was indeed selected because of its ability to overcome the limitations observed in other approaches. Thanks to its logic-driven structure rather than a data-driven one, it allows the inclusion of both qualitative and quantitative variables, making it suitable to support decision-making even when data availability is limited (Colombo et al., 2024).

In this context, the present study advances the literature in several ways. First, it replaces static, weight-based aggregation approaches with a logic-driven, simulation-based structure capable of modelling interdependencies and uncertainty propagation across the entire supply chain. Second, it integrates technical, economic, environmental, geopolitical, and societal risk factors within a unified framework, allowing these dimensions to interact dynamically rather than being evaluated as isolated indicators/criteria that are subsequently aggregated into composite scores (Mouloudi and Evrard Samuel, 2022). Third, it shifts the basis of supplier ranking from static composite performance scores to a risk-informed evaluation analysing risk distributions, resilience characteristics, and critical risk drivers. Finally, it applies this methodological structure specifically to mineral resource supply chains, addressing their structural conditions such as geological constraints, supply concentration, geopolitical exposure, and regulatory heterogeneity. By doing so, the study brings a systemic, risk-structure-based perspective to strategic procurement under conditions of high uncertainty.

3. The HoRAM method

The complex interaction between qualitative factors (e.g., geopolitical conditions) and quantitative factors (e.g., technical parameters), together with the dynamic nature of supply chains, requires a flexible methodology capable of accommodating uncertainty while providing transparent and practical insights. For these reasons, this study adopts the Holistic Risk Analysis and Modelling (HoRAM) method (Ciotola et al., 2021; Colombo, 2019) to create the aimed framework and the underlying previsional model.

Conceptually, HoRAM follows the ISO 31000 and can be understood as a dynamic, logic-based risk analysis approach. The method starts from a system characterisation performed from a risk perspective, identifying key variables that influence the achievement of defined objectives. Each variable is described through a set of possible logically consistent states, each associated with a probability of occurrence and with logical and phenomenological implications. By combining all possible variable states, HoRAM generates the universe of scenarios, each associated with a final cumulative probability and an overall impact that can be either positive (i.e. a gain) or negative (i.e. a loss). This allows the derivation of the risk profile of the system. In this sense, the method resembles an event tree, although the scenarios emerge from the combination of the variables, their states, and the logical and stochastic relationships encoded in the model.

The methodology consists of three main steps: 1) System Characterization, 2) Risk Level Identification, and 3) Risk Treatment, as highlighted in Fig. 2. The System Characterisation aims to understand the system or phenomenon under investigation and identifies the key variables (the so-called elective variables) and their relationships, forming the basis for subsequent modelling and iterative refinement. This step considers temporal dynamics and variable interactions and lays the foundation for the entire analysis. The Risk Level Identification involves the creation of the model, composed of its logic-stochastic and phenomenological components. The logic-stochastic component is made up by the variables and their possible positive and negative states, each associated with a probability of occurrence and a coefficient of variation. The phenomenological component defines the numerical impacts associated with each state, reflecting the consequences associated with the events described. This part of the model is defined by adopting a classical deterministic approach. By combining the two components, HoRAM ensures a consistent risk-based analysis, in line with the ISO 31000 definition of risk as the combination of probability and impact. Risk Treatment closes the iterative loop. The analysis identifies the variables that contribute most to the overall risk, not only in terms of probability but also in terms of impact. These critical variables enable the analyst to identify the most suitable mitigation measures and implement them into the model to verify their effectiveness. Typically, several iterations are performed to validate the mitigation strategies. The HoRAM method is implemented thanks to the cloud-based platform Klarisk® which performs the simulations.

4. The risks of the supply chain of cadmium to Germany: a case study

4.1. Step 1: system characterization

Cadmium is important in the manufacturing of certain solar panels, in particular in Cadmium telluride (CdTe) thin-film solar cells (Chu and Chu, 1993; Hor et al., 1983). CdTe photovoltaics play nowadays an important role in the diversification of solar-energy technologies. A key characteristic of Cadmium is that it is not mined directly, but it is obtained almost exclusively as a by-product of zinc refining, with smaller amounts found in lead and copper ores. This structural dependence on zinc production is widely recognised in the literature as a major source of supply risk, as Cadmium mining cannot be increased independently in response to market demand. The refining process involves several steps, including roasting the extracted Cd/Zn concentrate to produce Cadmium oxide. Further refinement through vacuum distillation or electrolysis separates Cadmium from other metals, yielding high-purity Cadmium. Cadmium is also toxic, and its extraction, processing, and disposal phases involve significant environmental, regulatory, and social risks (Hutton, 1983; Sadegh Safarzadeh et al., 2007; van der Voet et al., 1994). Due to the reasons mentioned, Cadmium represents an exemplary material for demonstrating the applicability of a holistic, multi-dimensional risk-assessment framework with HoRAM. Therefore, the study presents a comprehensive risk assessment of the supply chain of the entire value chain of Cadmium from extraction to refinement and, ultimately, presence in the market. In this analysis, different extracting countries are analysed while Germany was selected as both a refining and market site given its central position in the European economic landscape.

The first step when starting the analysis with the HoRAM method is to identify the objective of the analysis. The identified driving force for the modelling activity is the entire supply chain of the raw material, from the mining activity, performed in country “A”, to a refining process, performed in country “B”, to conclude with its arrival to a market site, all expressed in terms of cost per ton (€/ton). The risk in this case is therefore valued in the cost (€) per ton of raw material procured. The monetisation of the risk of supply allows for a better identification of opportunities, facilitates communication with stakeholders, and eases the data collection and the comparison among different suppliers and refining countries.

To conduct a comprehensive analysis of the sustainable supply chain of extracted raw materials, the authors conducted a detailed preliminary analysis focusing on the system characterization based on extensive literature research and the collaboration with a supply-chain expert. This step produced two main outcomes: a Functional Analysis (FA) and a

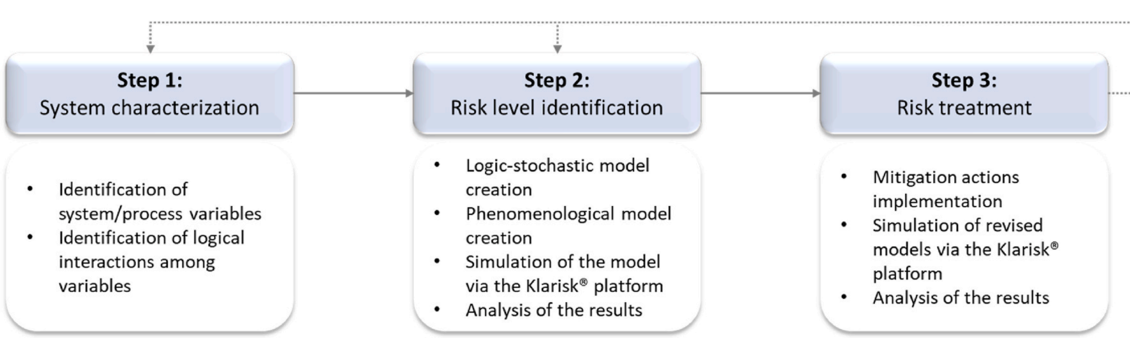

Fig. 2. Overview of the HoRAM methodology, its three main steps (system characterization, risk level identification, and risk treatment) and their iterative implementation.

detailed Gantt chart of the process examined. The FA allowed to systemically identify the main phases within the supply chain process. Four main stages were recognised: 1) mining process, 2) logistics from mining site to refining site, 3) refining process, and 4) logistics from refining site to the market. The objective was to comprehensively assess risks at each stage of the supply chain. Fig. 3 shows the high-level flow chart derived from the FA. The Gantt chart, available in the Supporting Information, further decomposed each phase into tasks and sub-tasks and allowed to visualize the interconnections among them.

A supply-chain expert validated the FA, the process sequence, and the list of primary descriptors associated with each stage during several semi-structured interviews. This ensured that the system representation and the selected descriptors captured the main socio-economic, environmental, political, technical, and logistical factors influencing supply-chain performance.

As a result, the performed preliminary analysis resulted in the identification of 350 variables, of which only a minority corresponds to auxiliary computational elements not subject to expert validation.

The variables are organised into levels, representing the step-by-step structure of the supply chain from upstream extraction to downstream market delivery. In the model developed here, the hierarchy reflects the structure of the Cadmium supply chain and includes blocks representing: (i) zinc ore extraction, (ii) ore concentration and transport, (iii) Cadmium refining, and (iv) logistics. For each block, the “levels” in the model correspond to the elective variables (e.g., mine permit approval, mine operation continuity, waste management performance, refining process availability, logistics disruption). The main descriptors characterising the supply-chain process across the four phases cover economic (e.g., CAPEX, OPEX, logistic costs, price fluctuations, etc.), societal (e.g., acceptance of the local communities of the mining activities, local employment, etc.), environmental (e.g., waste management, production of Acid Mine Drainage (AMD) in the mining site, presence of toxic or radioactive materials, carbon footprint, etc.), political (e.g., corruption of the country, political stability, trade policy, etc. reflecting broader geopolitical and regulatory conditions), and technical (e.g., technological advancement in the country, machinery breakdowns, etc.) dimensions. Fig. 4 graphically summarises the structure of the model.

4.2. Step 2: risk level identification

Once the preliminary analysis is performed and the elective variables identified, it is possible to proceed with the creation of the modelling structure, the simulation steps associated with it and the consequent analysis of the results.

4.2.1. Model creation

As previously mentioned, the study considers Germany as the market site; for this reason, the preliminary analysis began with the examination of countries that are nowadays major suppliers of zinc ore for Germany. Germany's zinc ore imports heavily rely on four nations, contributing to at least 75% of its total current import volume, namely: the United States, Australia, Sweden, and Peru (World Bank, 2021). For each mining country Germany was considered as refining site (subsequent step) and the generalised model was shaped accordingly. At the end of the process for each supply country one model was created, considering the country-specific probability of the variables and impact values.

The logic-stochastic part of the previsional model demands probability values for each selected variable. The authors derived the probabilities in three different ways, namely: 1) from internationally recognised indices (e.g., corruption index, World Governance Indicator, etc.), 2) from phenomenological considerations of known and quantifiable events (e.g., machinery breakdown, process interruption, material toxicity, etc.), and 3) from assumptions for all those events that are neither measured nor measurable. This choice was done to ensure a thorough understanding of the various risks involved. As an example of probabilities numerically derived directly from internationally recognised indexes, the Environmental Performance Index (EPI) was applied to assess the likelihood of effective mining waste management (Wolf et al., 2022). The EPI offers a data-driven foundation for environmental policy decisions by evaluating countries' ability to manage waste effectively. As an example of probabilities calculated based on available data, the probability of a truck accident was determined by analysing historical data on transport-related accidents in the relevant regions. Where data were available, and probabilities could be calculated, the model directly incorporated the empirical data available, ensuring stronger anchor points in the previsional approach. In those cases where specific data were missing or certain factors could be hardly estimated (e.g., the probability of having a mining permit rejected), probabilities were assumed also in relation to the available anchor points. These assumptions were made based on reasonable judgments, historical data (also those statistically not relevant), and expert judgment. Although some probabilities must be estimated due to limited data availability, these assumptions remain meaningful within a probabilistic framework. In line with the coherence principles of subjective probability theory (Finetti, 2017), HoRAM ensures that even approximate probability inputs lead to internally consistent results. This allows the model to remain robust under uncertainty and enables systematic sensitivity analysis for variables characterised by higher estimation uncertainty, thus guaranteeing a thorough systemic approach (cf. Supporting Information, Tables A1.1–A1.5).

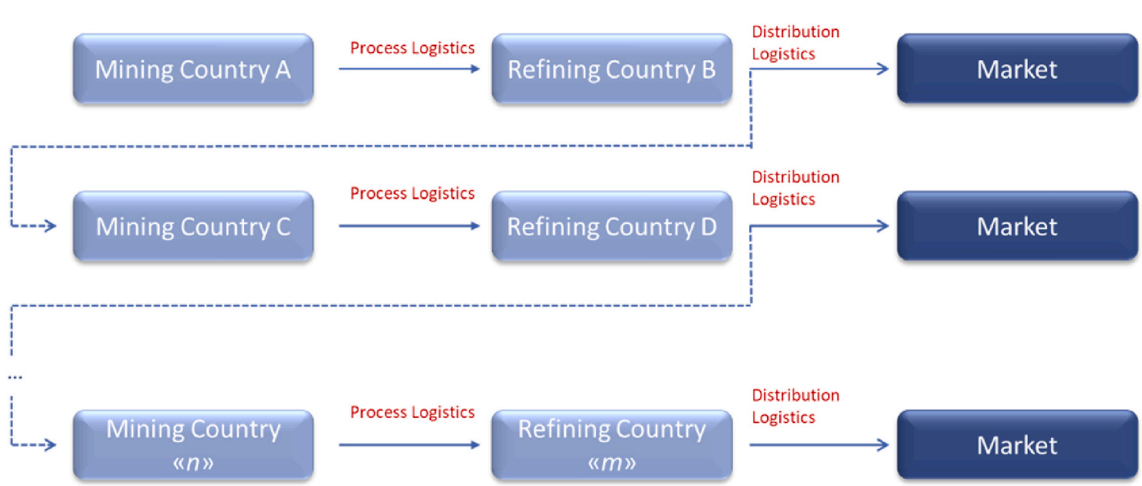

Fig. 3. Logic flow chart derived from the Functional Analysis of the supply chain of raw materials.

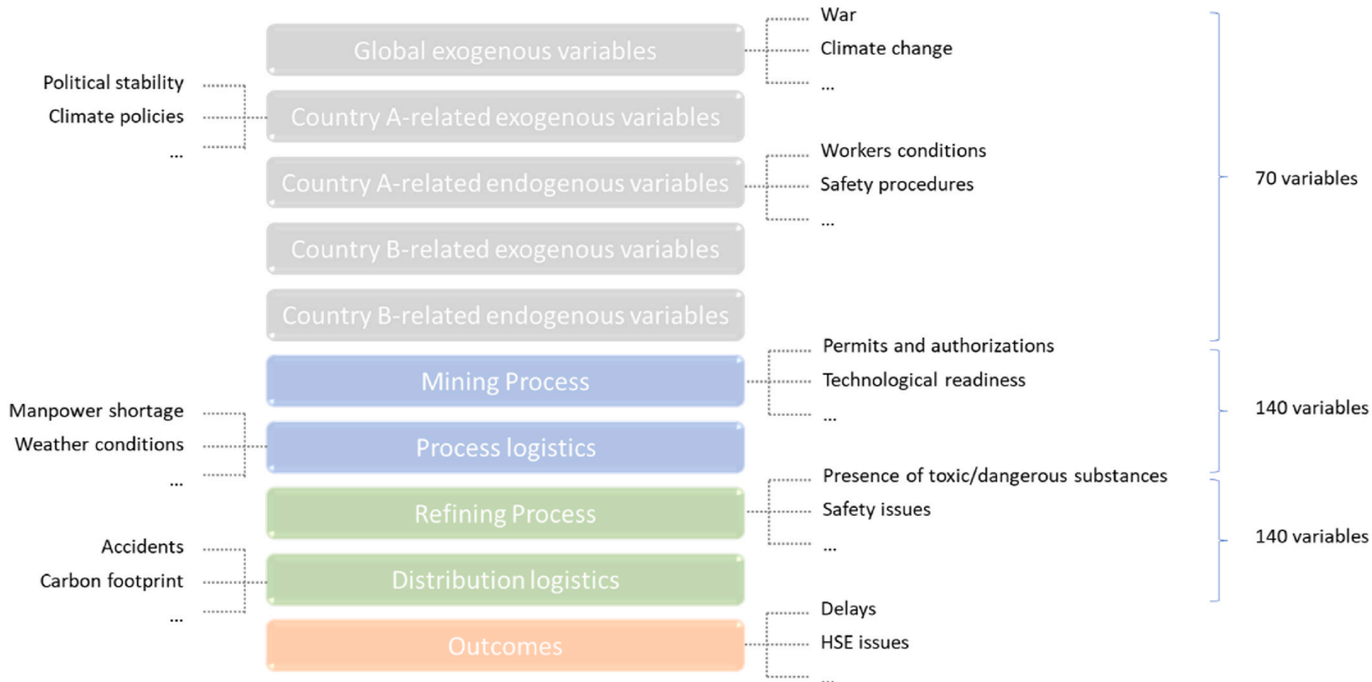

Fig. 4. Scheme of the model structure and variables subdivision. "Country A″ is the mining country while "Country B″ is the refining country.

For the phenomenological part, in the previsional model impact is denominated in terms of costs. To achieve this goal, representative companies from each mining and refining country were identified. The representativeness was based on the assumption that the chosen companies hold economic characteristic patterns and operational practices which are prevalent in their respective nations. As a proxy, the market share was used. Once the representative companies were selected, their Capital Expenditure (CAPEX), Operational Expenditure (OPEX), and annual production were derived, using companies' annual financial reports. The resulting cost per ton were then introduced into the model as impacts associated to corresponding variables. Logistics costs were calculated for specific transport routes between the supply country and Germany, estimating the total needed containers on base of the transported cadmium. The assumed containers are standard carrying capacity of a 40-inch container (approximately 32 tons). The model offers various transportation options (e.g., train, truck, plane, or ship), each associated with specific costs based on the selected mining, processing, and market sites.

For the United States the Doe Run Company, Wentzville, Missouri, was identified as a representative company; for Australia the Cannington mine (in Queensland), for Sweden the Boliden group, and for Peru the Cerro Lindo mine (near Pampa Chacra). The zinc ore extracted by these companies is then transported to Germany where is processed and refined at Glencore's facility in Nordenham, providing the needed Cadmium. The refined material is then transported to Munich, one of the major technology hubs of Germany. In the Supplementary Information the authors provide an overview of the probabilities employed in the logic-stochastic part of the model and of the impacts considered in the phenomenological part (cf. Supporting Information Tables A2.1–A2.4).

4.2.2. *Analysis of the results*

To perform simulations of complex systems in a reasonable timeframe and mostly efficient, it is recommendable to fence the probability space, i.e. to sort out those probabilities of occurrence is below a specified threshold and, thus, presumably not significant from a decision-making standpoint. The approach at HoRAM is to estimate the residual probability which cumulates the probabilities associated with discarded scenarios falling below the probability cut. To assess the appropriateness of the residual probability, the lowest probability associated with a variable is compared with that of the residual probability calculated by the algorithm as a consequence of the applied cut. Generally, the residual probability should be lower than the prevailing lower probability value assigned to variables. The more complex a system is, measured by number of considered variables, as a rule of thumb, the lower would be the required expectable difference, although a difference beyond one or two magnitudes is desirable. Ideally, the value of the residual probability is to be between two and three orders of magnitude lower than that of an event considered practically impossible from a decision-making standpoint (Colombo, 2019), which is seldom tangible for complex systems.

In the presented case, the lowest order of magnitude assigned to only one variable (i.e. accident involving operators and environmental hazards in the selected German refining company) was 1E-05, while the prevailing probability value is 1E-02. Ideally, this would require residual probabilities in the range of 1E-6 and 1E-7. However, such thresholds result in prohibitively high computational costs for the complexity of the system analysed. To balance computational efficiency and information retention, different probability cuts were tested and compared (Table 1). As results obtained with different cuts did not lead to significant changes in the decisional parameters, a probability cut of 1E−10 was selected as a suitable compromise, yielding acceptable residual probabilities with reasonable simulation times. This methodological procedure reflects a key feature of the HoRAM method: rather than discarding variables *a priori* due to computational constraints or low individual probabilities, HoRAM keeps all selected variables and filters out low-probability scenarios that are not relevant for decision-making purposes. In this way, the method preserves systemic completeness while maintaining computational feasibility.

Due to the high computational demand necessary to simulate the entire model (i.e., hours of simulation for universes with high residual probabilities in the range of 3E-1), it has been necessary to divide the model into two models, thus adopting a multi-phase approach. The first model was focused on mining and process logistics (i.e. the logistics between the mining and refining sites), while the second one on refining and distribution logistics (i.e. the logistic between the refining and the market sites). To prevent any loss of information, logical constraints and

Table 1
Overview of the effects on changes in the probability cut.

	Prob. cut	Universe	Residual Prob.	Minimum €/ton	Expected €/ton	Maximum €/ton
USA Mining + Process logistics	1.00E-08	113,373	7.90E-04	140.04	175.94	1616.42
	1.00E-09	295,292	1.86E-04	139.79	175.98	1618.35
	1.00E-10	726,459	4.14E-05	139.79	175.99	1622.25

Table 2
Overview of the universe size, residual probability and cost per ton associated with the supply chain of zinc ore from the different countries.

	Scenarios	Residual probability	Minimum €/ton		Expected €/ton		Maximum €/ton	
USA	726,459	4.14E-05	139.79		175.99		1622.25	
Australia	819,929	4.69E-05	158.07	13.1%	195.74	11.2%	1664.99	2.6%
Sweden	516,588	3.01E-05	93.03	−33.4%	188.61	7.2%	1713.73	5.6%
Peru	1,202,581	6.93E-05	154.52	10.5%	190.58	8.3%	1641.84	1.2%

stochastic conditionings between the two models were preserved. Given that, by initial assumption, the refining of the raw materials takes always place in Germany, the results of the second part of the model analysing the processing stage and the distribution logistics do not show significant difference among each other. Therefore, the results presented in this paper will only focus on the first part of the model which considers raw material's extraction and transportation to Germany. This procedure, anyway, respects the scope of the analysis given that the decision-making process of selecting the best supplier of raw materials for Germany happens looking at this stage of the process (i.e., when the raw material has to enter the country from abroad). Table 2 shows the results achieved with the simulations in terms of universe size (i.e. number of scenarios generated), residual probability, minimum, expected, and maximum cost per ton found for the different countries combinations. To have uniform and comparable levels of discarded information across all generated universes, it has been made sure that all residual probabilities were approximately the same. Despite this, one can notice that the size of the generated universes shows a certain variability (i.e. from 516,588 for Sweden to 1,202,581 for Peru). This can be explained by the fact that, despite the variables considered are the same for each country, the different set of probabilities and influences amongst variables (reflecting the characteristic of each country) affects differently the structure of the universe being generated in relation with the chosen probability cut. The appropriateness of the comparability amongst universes is ensured by the comparability of the residual probability, i.e. by the homogenous amount of information considered. To have a better vision of the results, in Table 2 it has been shown the costs for each country in relation to that obtained for USA, which has been taken as a reference to measure the increase or decrease resulted by the other countries.

Before analysing the numerical results in Tables 2 and it is worth clarifying that the goal of this analysis is to quantify risk costs factors associated with the procurement of Cadmium along its supply chain. Therefore, the results presented refer to risk-adjusted cost outcomes which account for potential cost deviations arising from uncertain events and their propagation across the system. Nominal costs, derived from accounting data such as CAPEX, OPEX, and logistics costs, are used exclusively as deterministic baseline inputs to the model and are not reported as standalone outcomes. While scenarios exist in which no adverse events occur and cost outcomes approach nominal values, the results presented always reflect risk costs generated by the full scenario space considered. Consequently, these values should not be interpreted as market prices or import costs of the raw material, as those are determined by various macro- and microeconomic factors beyond the scope of this study.

The minimum value of the cost per ton represents the best-case scenario. Conversely, the maximum value represents the worst-case scenario, where, for example, various accidents lead to significant losses and delays in production. The distance of the expected value from the max and min values reflects the tendency of the systems being analysed: the closer the expected value to the max, the higher the tendency of the system/phenomenon to manifest itself in a dangerous status. Analysing the current import strategy of Germany for Zinc ore,[1] it is possible to notice that the USA is the top supplier (in terms of tons supplied), followed by Australia, and Sweden as third option. The results of the analysis suggest that a different strategy would be more efficient. Actually, despite the USA would remain the most advantageous supplier for Germany, Sweden and Peru would emerge as second and third most preferable choice, leaving Australia behind due its higher risks. Specifically, Sweden shows the lowest minimum cost per ton (i.e. with a generous −33.4% with respect to USA), which is compensated by the highest maximum cost per ton (i.e. with a 5.6% with respect to USA but still high compared to the 2.6% of Australia and 1.2% of Peru). This result can be explained, on the one hand, by the country's proximity to Germany (i.e. logistics implications), and, on the other hand, by Sweden's high production and societal standards. Sweden and its market are highly reliable. Yet, this high reliability is achieved thanks to the high level of innovation adopted in the production processes and to the high societal standards applied in operating them (such as the strict waste management plans and the operational choices to reduce carbon footprint). Therefore, when something goes wrong, these same high standards, reflected in the costs outlined by the selected Swedish company (The Boliden Group) in their annual financial reports, easily result in higher recovery costs compared to the other countries analysed. From these considerations it can de deduced that the Sweden can be considered the second-best supply option for Germany.

Peru, which has an expected cost very similar to Sweden, shows a higher minimum cost per ton (compared to Sweden) primarily due to logistic costs and lower production and societal standards. The lower level of innovation of the productive processes (i.e., lower efficiency) is partly compensated by lower societal standards, reflected in a higher tolerance towards environmental pollution and lower labour market protection. When problems occur, the costs associated with such events in Peru are much lower than in Sweden. This makes Peru the third-best candidate for Zinc ore supply. Australia that has production and societal standards closer to Sweden (than Peru), is the one suffering the most the higher logistic costs (compared to Peru) as they cannot be compensated by significantly lower societal standards costs, thus making Australia the less appealing supplier of all.

Fig. 5 shows the comparison of Complementary Cumulative

[1] https://wits.worldbank.org/trade/comtrade/en/country/DEU/year/2021/tradeflow/Imports/partner/ALL/product/260800#.

Distribution Functions (CCDF), which is the curve that represents the risk level associated with the decision-making opportunity being analysed. In the abscissa is reported the impact (in this case €/ton) while in the ordinate is indicated the probability value of exceeding the chosen impact value. The lower the curve, the lower the risk (i.e. the cost). In the case analysed, Fig. 5 represents the cost associated with the first part of the model analysing the mining countries and process logistics. From the CCDFs comparison of Fig. 5, even if the curves are quite overlapping, it is possible to notice that the blue curve, representing the USA, is the lowest throughout nearly the entire magnitude axis (abscissa), except for the three circled points where the red curve (i.e. Sweden) is lower. This suggests that USA provides the best results with the lowest associated risks (i.e. cost/ton). Therefore, it can be concluded that USA may be the most advantageous source for Zinc ore imports for Germany, considering its low-risk and high-performance outcomes. Fig. 6 shows the second and most important decision-making tool that is the Risk Distribution Function (RDF), graphically representing the risk profile. The RDF shows how the created scenarios distribute within the 100 homogenous classes the consequence range is divided into (by the algorithm). The higher the class, the higher the number of scenarios included in it and, consequently, the higher the resulting risk and probability associated with the class. The RDFs comparison shown in Fig. 6 represents the results achieved with the first part of the model analysing the three primary countries involved in the mining of Zinc ore and their logistic process till Germany, namely: the USA (blue), Sweden (red), and Peru (green). These three countries were selected based on their respective risk outcomes as discovered in our study based on the preliminary results readable in the risk parameters of Tables 2 and in the compared CCDFs of Fig. 5. The USA demonstrates to be the most favourable supplier, while Sweden and Peru concur for second and third place.

The results between the three countries appear closely connected. However, on deeper analysis, differences in risk contribution become clear. The presence of red bars (Sweden) across the graph is immediately noticeable. In fact, red bars appear to be usually taller and more numerous both on the left and right sides of the graph, denoting the possibility to have both lower associated costs than the other countries, but, also, higher. Indeed, this is the graphical translation of the fact that Sweden shows the lowest possible minimum cost and the highest maximum. This risk profile shows why the expected cost value is shifted and results being higher than the one found for the USA. On the contrary, the USA (blue) classes are less numerous and primarily clustered within the graph's left side, meaning lower impacts. This distribution shows that the USA's risk contribution to high values (of costs) is lower than the other countries. For Peru (green) the classes are present on both sides of the graph as it was for Sweden but are shorter and lower in number than the red ones. In fact, on the left side of the graph if the red classes have two breaks, the green ones are denser (i.e. cover nearly the full axis range). On the right side the green classes appear to be less dense and shorter than the red ones. Moreover, Peru is the only country that shows classes also in the middle-range impacts, at the centre of the graph. This gives the message to the decision maker that, should something go wrong, and costs will have to increase, it is reasonable to expect them to fall also in the little range of 800-900 €/ton where green classes are placed. This behaviour is different from that of USA and Australia for which costs can be expected to be either from 450 €/ton downwards or from 1380 €/ton upwards for USA and from 500 €/ton downwards or from 1330 €/ton upwards for Sweden. Peru experiences several issues, comparatively more than the USA and Sweden, but the costs associated with these issues are relatively lower. This makes Peru a viable suppling option, balancing moderate risk with competitive costs. Fig. 7 shows a highlight of the RDFs of USA, Sweden and Peru.

To efficiently and effectively act on the variables that have a higher risk contribution to the overall supply chain, the other essential decision-making tool provided by the method is the Critical Function List (CFL). Table 3 shows the CFL for zinc ore mining in the USA, with the mined ore used for subsequent export to Germany for refinement into Cadmium.

As it can be noticed, the major risk-contributing variable is the "Geophysical data" in the condition of "Sub-surface mining". This indicates that the adoption of sub-surface mining due to geological needs elevates the risk contribution above all other variables considered in the model. This variable, indeed, intensifies the overall impact in case of problems and thereby the resulting costs. In fact, sub-surface mining requires excavation and tunnelling, which can lead to great environmental impact, as well as potentially higher health and safety implications. Moreover, sub-surface mining, if not properly managed, can lead to groundwater contamination that, in turn, can impact local water

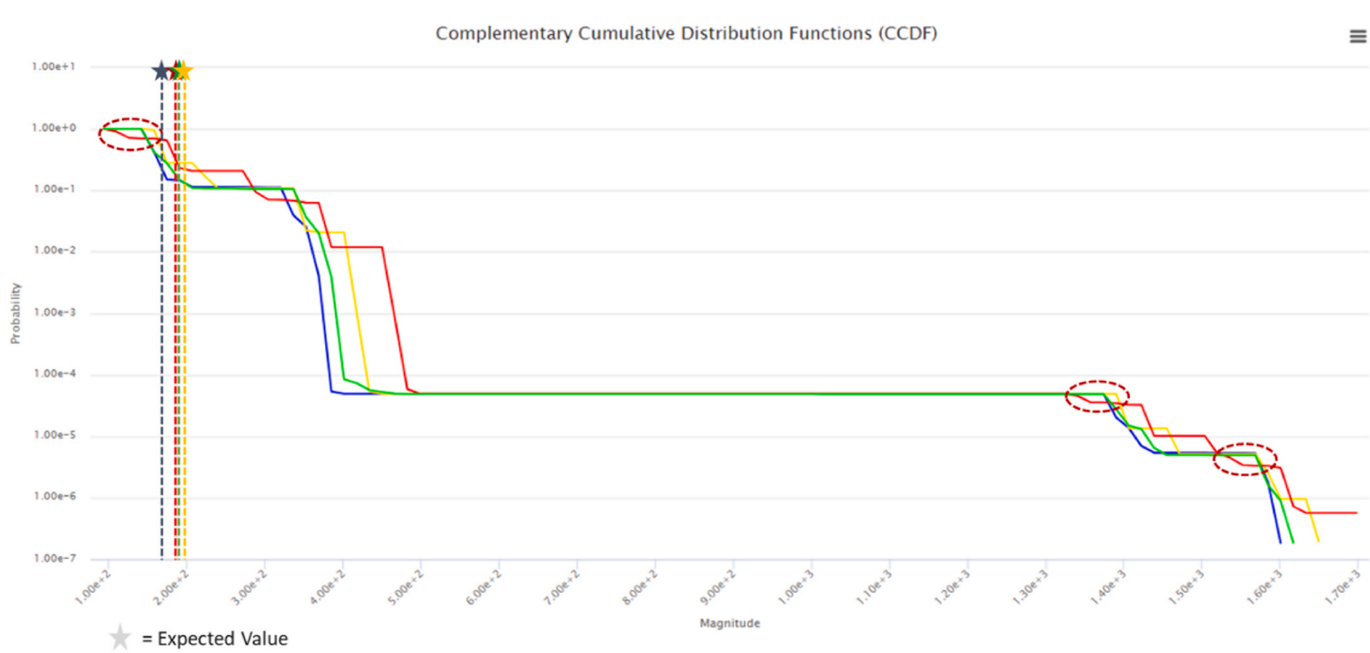

Fig. 5. CCDF for Cadmium showing USA (blue), Australia (yellow), Sweden (red), and Peru (green). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

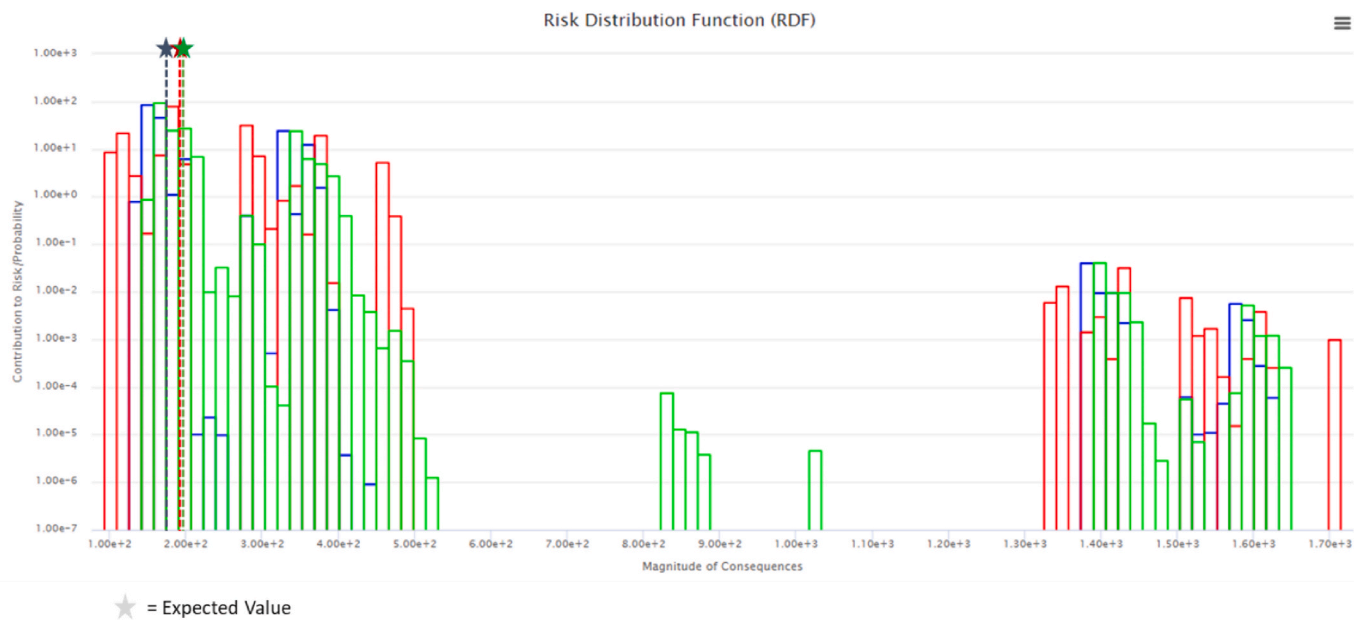

Fig. 6. RDF for Cadmium showing USA (blue), Sweden (red), Peru (green). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

supplies and ecosystems. The energy-intensive nature of sub-surface mining operations also contributes to higher greenhouse gas emissions compared to surface mining, exacerbating climate change implications. All these aspects are taken into consideration in the model both by increasing the probability of occurrence of accidents and environmental issues (stochastic side) and by adding additional costs (phenomenological side). For these reasons, the risk contribution from the sub-surface status of geophysical data contributes alone to generate a remarkable 80% of the overall risk. The next significant risk-contributing variable is "Weather conditions", specifically when it is in the "Not favourable" state. This is expected to contribute for another 5% of the overall system's risk, which cumulatively gives the 85% of the risk. This because adverse weather conditions can further complicate sub-surface mining operations, increasing the overall mining activity. Indeed, heavy rainfalls can lead to flooding within mines, while extreme temperatures can affect both machinery efficiency and workers' health and safety. In the Supporting Information it is possible to see the CFLs of the other mining countries, where it is possible to notice similar trends to the one presented.

4.3. Step 3: risk treatment

Risk treatment is the last step in the risk engineering process. In this phase, the analyst can modify the model's logic-stochastic and/or phenomenological components to observe how the system reacts. In order to highlight the importance of a holistic view when performing a risk assessment that considers the dynamic interrelations of the variables, the authors present two examples of how to perform this step: a "stress analysis" to evaluate the system's resilience to external disturbances, and a scenario analysis where different initial assumptions are introduced to explore the system's behaviour under new conditions.

4.3.1. Stress analysis

In this section is shown how the system reacts to external disturbances, thereby providing insights into the characteristics of the model and the information that can be available to stakeholders when using a systematic approach. To that end, the variable "Climate Change" has been switched to the "Affect" state. The activation of this variable has the following implications: a tightening of climate and environmental policies, which may impose new constraints to operations; an increase of the probability of facing unfavourable weather conditions, potentially upsetting regular operations; an increase in the frequency of strikes and protests, leading to a higher delay. By analysing the system's response to these stressing conditions, the aim is to understand the resilience of the system to disturbances, providing a comprehensive and holistic perspective on its performance.

Table 4, which is an updated version of Table 2, modified based on the results in the stressed conditions, shows that the stressing conditions do not modify the supply priority as USA stays as primary choice. From a decision-making standpoint, this means that the decision is resilient towards the aforementioned climate change-related conditions.

One aspect that stands out in the table is the impact of the three stressing conditions on the cost (€/ton) as they are expected to lead to an increase of production costs for all countries examined, although with different magnitude. For instance, the cost increase in the expected value for the United States is estimated to be 2.5%, while that for Australia 8%. Sweden would have an increase of 0.4%, and the most significant increase would be for Peru, with an increment of 17.6%. These changes underline the potential economic implications of stressing conditions within the supply chain model. In particular, it is possible to notice which countries show more stable behaviour (i.e. USA and Sweden) compared to others that are more affected by external factors (i.e. Australia and Peru). Moreover, due to a change in external conditions caused by climate change effects, the ranking of the best supplier countries for Zinc ore changes. Peru now appears to be the worst option in terms of minimum and expected cost. No significant changes have been noticed in the CFLs of the different countries, while CCDFs and RDFs present changes in compliance with the results highlighted by Table 4. The Supporting Information shows the other results under stressed conditions in comparison to the nominal cases.

4.3.2. Scenario analysis

Scenario analysis can be used to assess the effects of different initial assumptions or variables on the system, thus exploring various starting situations. To better understand how environmental factors could impact the decision-making process, this study proposes a scenario where the carbon footprint no longer contributes to the cost of the supply chain. In the reference situation, direct carbon emissions impacted the cost based on a carbon price set, when as expected, at €36 per ton of CO_2. In this scenario analysis, the contributing cost is assumed

Fig. 7. Highlight of the RDFs of A) USA, B) Sweden and C) Peru.

Table 3
Critical components for USA – zinc mining.

Priority	Variable name	Variable status	Risk %	Cumulative risk %
1	Geophysical data	Sub-surface mining	80%	80%
2	Weather conditions	Not favourable	5%	85%
3	Mining activities CAPEX	Not as expected	4%	89%
4	Mining activities OPEX	Not as expected	3%	92%
5	Waste management plan	Not properly applied	2%	95%

Table 4
Overview of the universe, residual probability and cost associated with the supply chain of zinc ore after the stress analysis for the different countries in relation with the reference case.

	Universe	Residual probability	Minimum €/ton		Expected €/ton		Maximum €/ton	
USA	1,111,808	6.36E-05	143.28	2.5%	180.46	2.5%	1623.81	0.1%
Australia	891,090	5.08E-05	172.96	9.4%	211.45	8.0%	1908.91	14.6%
Sweden	516,588	3.01E-05	95.10	2.2%	189.35	0.4%	1713.71	-
Peru	1,302,275	7.56E-05	187.58	21.4%	224.07	17.6%	1674.89	2.0%

to be zero, allowing us to observe the system's behaviour without the influence of the carbon footprint.

Table 5 shows the results obtained with this analysis in comparison with the ones of the nominal case reported in Table 2. It is possible to notice how much the carbon footprint was contributing to the cost of the Cadmium supply chain for Germany. Among the analysed countries, Peru had the highest contribution from the carbon footprint, followed by Australia, USA, and Sweden. It is worth noting that, while the carbon footprint accounts for approximately 1% of the cost per ton of material, this percentage becomes significantly more impactful when considering the annual production and supply of Cadmium. The results achieved for Peru seems to confirm the lower standards adopted in the country for their production process, resulting in higher greenhouse gases emissions and, consequently, in higher CO_2 costs.

Another important point that is deduced from these results is that if decision-makers would have selected the supplier countries solely based on the overall costs and uncertainties of supply (as for this scenario), their choice would have been misleading. Actually, to be sustainable, a decision-making process must be capable to evaluate the weight of each ecological aspect into the decision-making process, such as the impact on the environment, the local community, the health and safety of workers, and not just assessing the gross economic results. From the results, while the USA keeps its position as top supplier, Peru would have emerged as the second-best option, surpassing Sweden. Yet, this conclusion is arrived at only when considering the overall costs and uncertainties. Managing scenario and looking at the decision-making problem from different view angles (i.e. taking into consideration the emissions as per the nominal condition presented in Table 2), it is possible to appreciate how the efforts made by Sweden in terms of environmental impact adding to the benefits of its proximity to the refining and market (i.e. Germany), play a crucial role. Therefore, a decision, to be sustainable, must allow to quantify both market and non-market risks and, more specifically, ought to compare competitors on an even weight basis for all non-market risks. Thus, the necessity of integrating environmental, social, economic and technical factors to ensure a holistic and sustainable approach in strategic supply chain decisions. In the specific case analysed, rewarding Peru, in the sense of choosing it as second-best supplier, only based on the overall production costs without digging into what is composing the overall cost structure, would imply to foster a player that is compromising on non-market risks to compete, thus compromising the sustainability of the decision.

5. Discussion

5.1. Interpretation of the results

The analysis shows that while some suppliers, such as the USA, perform robustly across both reference and stressed scenarios, other suppliers exhibit changes in their relative prioritization once adverse conditions are considered, highlighting the limitations of decisions based on nominal conditions alone. The results demonstrate also that similar risk-adjusted costs may be grounded on different risk structures, with distinct underlying drivers and mitigation feasibility, a distinction that becomes visible only through scenario-based analysis and the identification of critical functions. Finally, the scenario analysis reveals that environmental considerations play a decisive role in supplier ranking. Excluding environmental cost components, such as CO_2-related costs, leads to a markedly different prioritization of supplying countries, potentially favouring options that bring higher systemic risks in the long term.

The results of this study offer several insights into how holistic risk assessments can support strategic decisions on raw-material procurement. Under the modelled conditions the analysis confirms that supplier selection shall not be based solely on average production costs or logistical advantages, but must also account for systemic risk, sustainability, and resilience considerations, in line with previous findings in supply chain risk and sustainability literature (Christopher and Holweg, 2011; Lee, 2009; Mangla et al., 2015). Indeed, in the presented case, supplier evaluation changes significantly when decisions are informed not only by nominal costs, but by risk costs derived from the full spectrum of scenarios generated by the system, in line with previous studies highlighting the relevance of scenario-based and risk-informed

Table 5
Overview of the universe, residual probability and cost associated with the supply chain of zinc ore after the scenario analysis for the different countries in relation with the reference case.

	Universe	Residual probability	Minimum €/ton		Expected €/ton		Maximum €/ton	
USA	726,459	4.14E-05	138.92	−0.6%	175.12	−0.5%	1622.25	-
Australia	819,929	4.69E-05	154.35	−2.4%	192.01	−1.9%	1661.26	−0.2%
Sweden	516,588	3.01E-05	93.02	−0.02%	188.59	−0.01%	1713.71	−0.001%
Peru	1,202,581	6.93E-05	146.26	−5.3%	182.32	−4.3%	1633.58	−0.5%

approaches in supply chain decision-making (Christopher and Holweg, 2011; Lee, 2009; Pujawan and Geraldin, 2009).

The presented scenario-based risk analysis reveals how different countries are characterised by distinct risk profiles under a variety of operational and external conditions, providing a more reliable decisional basis than static cost indicators or criticality matrices. This is particularly evident in cases where estimated risk costs are comparable, yet the underlying risk patterns differ substantially, as observed for the case of Sweden and Peru. Sweden can be characterized by high environmental, safety, and societal standards, which increase nominal costs but simultaneously reduce the vulnerability to institutional and operational disruptions. These standards function as stabilising mechanisms: they limit the probability of severe failures and enable more effective absorption of external shocks, ultimately making the system more reliable in the long term. Peru, on the other hand, shows lower nominal costs, but presents a higher sensitivity to external factors such as climate-related events, social unrest, or permitting delays, as the standards are less mature. This means that even small disturbances can shift the system rapidly towards less favourable outcomes. The relevance to disclose risk pattern systematically for decision-processes is confirmed by the discussion in literature (Ioannidou et al., 2019).

The application of the framework to the Cadmium supply chain further illustrates how the identification of critical functions enables a deeper interpretation of country-specific risk profiles. The identified CFLs reveal that the dominant risk-contributing variables differ across supplying countries, reflecting structural characteristics such as institutional maturity, environmental and safety standards, and exposure to external disturbances. For instance, in the case of Sweden, the first critical functions identified at the mining stage are predominantly associated with structural system properties which contribute to higher nominal costs. In contrast, for Peru, the presence of capability-related variables, such as technological readiness, among the top critical functions indicates that internal inefficiencies can act as key risk drivers. This implies that relatively moderate disturbances, whether internal or external, may propagate more easily through the upstream system, resulting in higher overall vulnerability. This goes beyond classical assessments, which typically quantify risk but do not specify where risk originates or which elements of the supply chain offer strategic points for mitigation (Ioannidou et al., 2019; Lee, 2009). Through the CFLs, it is possible to highlight the factors that drive the risk in each country. This enables decision-makers to focus their mitigation strategies precisely where they matter most, improving efficiency, efficacy, and strategic planning. Moreover, by comparing countries through the lens of their critical functions, it becomes clear which suppliers present risks that are manageable through targeted mitigation actions, and which ones present structural vulnerabilities that are difficult, or economically unreasonable, to mitigate.

The proposed approach allows to broaden the scope of risk assessment which goes beyond the traditional cost- or price-oriented perspectives by explicitly integrating environmental, socio-political, and technical factors. In the present case study, this is reflected, for example, in the upstream supply from Peru, where variables related to technological readiness interact with permitting procedures, social stability, and climate-related disturbances, leading to a higher sensitivity of the mining stage to relatively moderate shocks. These results illustrate that supply disruptions rarely arise from isolated technical failures or price fluctuations alone but rather emerge from the interaction of multiple system dynamics (Kleindorfer and Saad, 2005; Tang, 2006). The explicit integration of socio-political and regulatory variables allows the framework to capture dynamics typically associated with the increasingly volatile international environment. Variables such as political stability, corruption, regulatory uncertainty, permitting procedures, and exposure to external disturbances (e.g., trade restrictions, social unrest, or geopolitical conflicts) are embedded in the logic-stochastic structure of the model and influence the probability configuration of the supply chain. This modification of the probability structure is reflected in the resulting risk curves, leading to shifts in the CCDF and RDF profiles that drive the comparative evaluation of supplying countries. As a result, changes in the geopolitical or regulatory context do not merely act as external qualitative considerations but can alter scenario generation, risk distributions and spectra, and ultimately the relative attractiveness of supplying countries thereby enabling a dynamic modelling of interdependencies and scenario-based analysis that goes beyond static, weight-based approaches. Through stress and scenario analyses, decision-makers are able to explore how shifts in environmental regulation, institutional stability, or trade conditions may propagate risks along the value chain and reshape procurement decisions.

5.2. *Strategic and policy implications*

The results suggest that the adoption of a holistic, scenario-based risk assessment framework could imply structural changes in procurement practices and resource governance strategies at both firm and national levels.

At the firm level, the adoption of a holistic, scenario-based risk assessment framework for the supplier selection provides the possibility to move beyond periodic cost optimisation exercises toward more continuous risk-informed portfolio management. Rather than evaluating suppliers primarily on expected costs or historical reliability, procurement sections would systematically include scenario-based stress testing, identification of crucial factors, and resilience indicators into decision processes. This enables firms to anticipate how geopolitical disruptions, regulatory shifts, or environmental constraints may propagate along the supply chain and to design contingency strategies accordingly. Such strategies may include diversifying suppliers not only geographically but also in terms of their underlying risk profiles, establishing long-term partnerships with institutionally stable countries, and directing investments toward addressing the specific vulnerabilities identified through the model's critical function analysis. Including such assessments at early stages of technology development would further allow companies to align material selection and sourcing strategies with long-term resilience considerations, reducing path dependency and exposure to structural vulnerabilities.

At the national level, the framework offers a complementary instrument to existing criticality assessments and raw-material strategies. Instead of relying on criticality rankings, governments could use scenario-based risk modelling to evaluate alternative sourcing pathways, simulate disruptive events (e.g., trade restrictions, geopolitical conflicts, regulatory tightening) within a comprehensive and interrelated setting, and, based on the gathered risk exposure, develop contingency plans. This would support the design of policy mixes combining trade diplomacy, strategic stockpiling, diversification incentives, and domestic processing capacity development. Periodic reassessment would be particularly relevant in a volatile international environment, allowing governments to update procurement strategies as geopolitical and regulatory conditions evolve.

Beyond risk mitigation, the framework also allows risks to be interpreted as potential opportunities. The identification of structurally manageable risk drivers may reveal supplier countries where targeted cooperation, infrastructure improvement initiatives, or technological partnerships could reduce vulnerabilities over time and foster new trade corridors. In this sense, holistic risk assessment becomes not only a defensive instrument but also a proactive tool for strategic positioning.

Finally, the widespread adoption of such framework may incentivize improved data transparency and international reporting standards. As risk modelling requires operational, environmental, and governance data, governments and institutions could play a role in enhancing data availability and harmonization, thereby strengthening the quality and comparability of risk assessments.

5.3. Limitations and further developments

Although logic-driven, the broadening of the scope of the analysis beyond traditional approaches, demands for a comprehensive data set which includes data from different sources, ranging from operational data to national and international legal data as well as macroeconomic data. The availability, quality, and granularity of such data inevitably vary across countries and domains. However, this does not constitute a fundamental limitation of the approach, as HoRAM is explicitly designed to operate under conditions of data scarcity, imprecision, and partial knowledge (Colombo et al., 2024). In the presented framework, nominal cost data serve only as deterministic baseline inputs, while the primary outputs of interest concern relative risk distributions, scenario structures, and the identification of critical functions. As a result, the absolute values of procurement costs should not be interpreted as precise market prices, but as risk-adjusted indicators reflecting the internal logic and interactions of the system. To ensure comparability across suppliers, all countries were modelled using the same type and quality of data (e.g., publicly available financial reports and internationally recognised indices), thereby subjecting them to the same degree of uncertainty. While absolute cost levels may vary if alternative datasets are adopted, the relative ordering of risks, the shape of the risk distributions, and the composition of the critical function lists remain stable, as they depend primarily on the logical structure of the model and the relative weighting of variables rather than on exact numerical values. This confirms that the strategic insights derived from the analysis are robust from a risk perspective, even when precise cost quantification is not possible.

To translate risks to one (monetary) unit allows for a comprehensive comparison of the risks in different countries. The presented study follows a common and widely approach in comparative studies (Christopher and Peck, 2004; Kleindorfer and Saad, 2005; Tang, 2006). But it is also a critical approach. Although in international trade only a small number of currencies are relevant, which includes the Euro, the local costs are influenced by the development of national currencies. These could change over time, influencing the relative cost position of each country and thus the relative risk position (Donnenfeld and Haug, 2003; Richmond, 2015).

Translating risks which are connected with human integrity or environmental damages into a monetary value raises ethical questions but also methodological challenges. Beside the question whether human integrity and integrity of the ecosystem can be valued – which is done in practice –, for modelling risks the challenge is how to value the integrity and to what extent national circumstances shall or shall not influence the estimated value (Hammer, 2012). The literature does not provide a single, universally accepted approach for estimating damage costs, but rather a wide range of methods and values, often based on willingness-to-pay and willingness-to-accept concepts, which are known to be sensitive to spatial, temporal, and socio-economic contexts (Hanemann, 2003; Viscusi and Aldy, 2003). To facilitate comparability across different supplying countries, the present study adopts a consistent valuation framework for accident-related impacts based on the occupational safety cost model developed by the U.S. National Institute for Occupational Safety and Health (NIOSH) (Heberger J. R., 2019), with implementation details provided in the Supporting Information. This approach estimates the economic consequences of fatal accidents in terms of medical costs, productivity losses, and associated indirect costs, and is widely applied in industrial safety and mining risk assessments (Biddle and Keane, 2011; Leigh, 2011; Miller, 1997). Accordingly, the monetary representation of human integrity impacts is used here as a normalization tool for comparative risk analysis rather than as a normative valuation of human life.

To further improve the analysis, it would be possible to include variations in the exchange rate and consider the covariation coefficient for each considered probability value, thus allowing to improve the uncertainty management in the modelling structure and moving from a discrete approach, as in the presented framework, to a continuous one.

The study applied the proposed methodological framework and the created previsional model to a single case involving Cadmium. However, the model has the capability to analyse various materials and supply chain configurations. For simplicity, the authors have chosen to focus on countries currently supplying zinc ore to Germany. However, it would be interesting to explore alternative strategies, including countries abundant in the searched material but not currently part of the suppliers' portfolio. This expansion of the analysis could provide valuable insights into alternative sourcing options and enhance the comprehensiveness of the model's applicability.

6. Conclusion

This research presented a systemic and systematic approach towards the understanding, the analysis, the quantification, and the management of risks associated with the supply chain of raw materials. Raw materials extraction and supply can have complex environmental and socio-economic repercussions, particularly in emerging economies. Illegal extraction practices, for example, pose direct environmental threats through alterations in landforms and pollution, which can subsequently impact local communities. This study highlighted the importance of adopting a holistic assessment, by taking into consideration all possible dimensions related to the supply chain, showing that the lower cost is not always synonym of sustainable decision. By reproducing this complexity within a structured framework, the proposed approach generates insights that are more robust and more aligned with the challenges faced by companies and policymakers. Indeed, the proposed framework is particularly suited to strategic procurement units of large downstream industrial actors in resource-importing economies, where long-term supplier selection decisions must integrate supply security, sustainability objectives, and geopolitical considerations. Beyond this primary application, the framework may also support policymakers and other stakeholders engaged in mineral governance and sustainability planning.

By applying the Holistic Risk Analysis and Modelling (HoRAM) methodology, the study provided a comprehensive exploration of the potential scenarios across different levels of the supply chain, emphasizing the role of an effective risk engineering and management for a sustainable supply chain of raw materials. The Cadmium case study, with Germany as refining and market site, showed what are the insights that it is possible to obtain by using a structured risk-based decision-making approach. For managers, the results highlight the importance of integrating scenario-based risk analyses into supplier evaluations, moving beyond comparisons based solely on expected costs and static risk assessments. For policymakers, the study underlines the need to incorporate systemic risks, governance conditions and environmental performance into raw-material strategies and trade partnerships, complementing current criticality assessments. Together, these insights support more resilient and sustainable procurement decisions.

In summary, this research offers an in-depth understanding of the raw material supply chains, putting the light on potential threats, opportunities and system's resilience under stressed conditions. While it paves the way for more informed and sustainable decisions, it also recognises the opportunities for future growth and development in the research area. Furthermore, by revealing structurally manageable risk drivers, the framework can help identify opportunities for strategic cooperation and targeted investment, turning potential vulnerabilities (comprising geopolitical threats, hazards, and structural weaknesses) into opportunities for building long-term supply chain resilience.

CRediT authorship contribution statement

Angela Ciotola: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Simone Colombo:** Formal analysis, Methodology, Software, Supervision, Validation, Writing – review & editing. **Ahmed I.Z. Elmenshawy:** Data curation, Investigation, Visualization. **Maryegli Fuss:** Conceptualization, Investigation. **Witold-Roger Poganietz:** Conceptualization, Resources, Supervision, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.resourpol.2026.105932.

Data availability

Data will be made available on request.

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