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Critical systemic risk sources in global lithium-ion battery supply networks: Static and dynamic network perspectives

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Abstract

Due to the indispensable role of electric vehicles (EVs) in achieving carbon neutrality, lithium-ion batteries (LIBs) for EVs have attracted considerable attention in the context of a widely distributed raw material supply and cross-border LIB production. Most previous studies have focused on only one specific LIB-related commodity supply, ignoring the intricate dependent relationships among mineral resources, intermediate components, and finished products. To fill this gap, this study employs a multilayer network model to construct the global EV-LIB supply network from 1990 to 2020 and explores critical risk sources from static and dynamic network perspectives. From the static perspective, the results based on the MultiRank algorithm reveal the critical position of countries, which are covered by single-layer-based indicators. The EV-LIB industry is shifting from upstream mineral resources to intermediate components and finished products (EV-LIBs and anodes). From the dynamic perspective, the impacts of risk sources and their risk transmission paths are revealed by the proposed dynamic shock propagation models under two realistic scenarios, i.e., supply restrictions on a specific commodity and blocked export channels. Some unremarkable shocks to a specific upstream commodity are revealed to have a substantial influence on downstream processes. Different effects of improving a country's anti-risk capacity on strengthening the robustness of the trade system are shown. The findings provide anti-risk support for policymakers seeking to hedge supply risks, adjust industrial planning, and ensure industrial safety.

Highlights:

- The global EV-LIB supply network is explored based on a multilayer network model.
- The influence of countries and commodities is assessed in the multilayer network.
- The impacts of supply restrictions are assessed based on shock propagation models.
- The sensitivity of fragility to a country's anti-risk capacity has three patterns.
- Hidden risks caused by supply restrictions imposed by core countries are revealed.

Keywords: EV-LIBs; Supply networks; Multilayer networks; Shock propagation; Risk sources

Word count: 7985

Abbreviations

EVs	Electrical vehicles
LIBs	Lithium-ion batteries
GELSN	Global EV-LIB supply network
COVID-19	Coronavirus disease 2019
MFA	Material flow analysis

Nomenclature

t	Year
l	Single layer
$G^{[t,l]}$	Single-layer network of layer l in year t
$V^{[t,l]}$	Countries of layer l in year t
$E^{[t,l]}$	Set of trade relationships between countries in layer l in year t
$\mathbf{W}^{[t,l]}$	Weight matrix of layer l in year t
$\mathbf{A}^{[t,l]}$	Adjacency matrix of layer l in year t
$MG^{[t]}$	Multilayer directed network in year t

$SG^{[t]}$

Set of single-layer trade networks in year t

$CE^{[t]}$

Set of directed links between the same nodes in different single-layer trade networks in year t

$PG^{[t]}$

Multiplex network in year t with undirected edges

$PE^{[t]}$

Set of undirected edges between the same nodes in different single-layer networks in year t

p_i

Centrality of node i

$z^{[l]}$

Influence of layer l

$s_j^{[t,l]}(in)$

Original in-strength of node j in single-layer network $G^{[t,l]}$

$s_i^{[t,l]}(out)$

Out-strength of node i in single-layer network $G^{[t,l]}$

$r^{[t,l]}$

Threshold of the anti-risk capacity of countries in layer l in year t

$as_i^{[t,l]}$

Number of avalanched nodes in layer l in year t shocked by risk source i

$is_i^{[t,l]}$

Number of iterations in layer l in year t shocked by risk source i

$VA_i^{[t,l]}$

Avalanched node set in layer l in year t shocked by risk source i

$am_i^{[t,l]}$

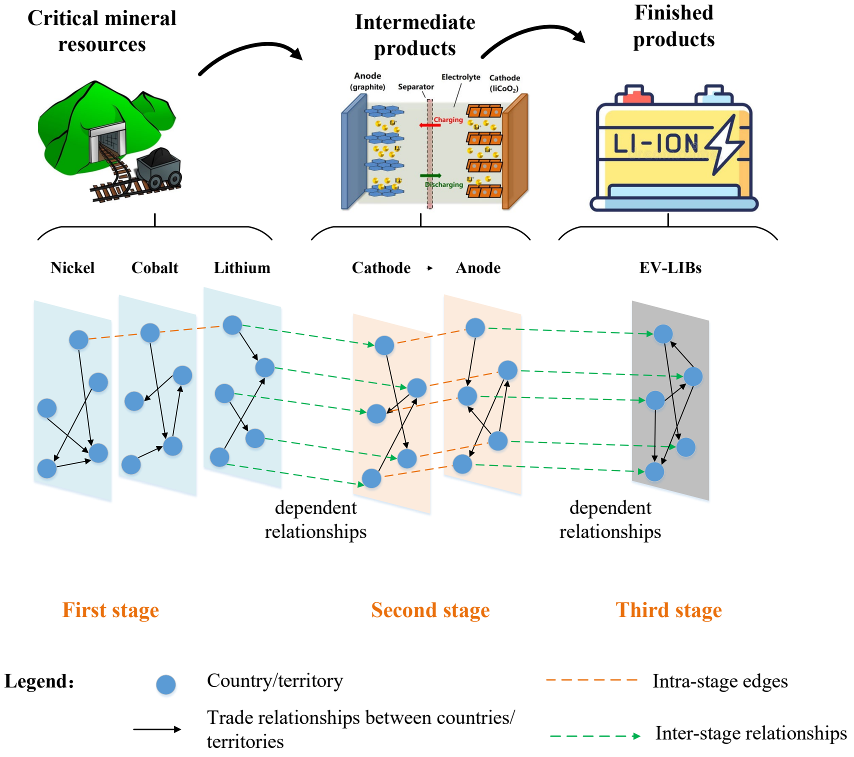
Number of avalanched nodes in layer l in year t shocked by risk source i

1. Introduction

Achieving carbon neutrality by the mid-21st century is essential for limiting global warming well below 1.5°C or 2.0°C. This target requires joint efforts from all sectors to develop a renewable and sustainable energy system [1, 2]. Transportation will account for 24% of direct CO_2 emissions from fuel combustion in 2020 [3], which deserves considerable attention to reduce CO_2 emissions [4]. The transformation of the transportation sector will require clean fuel solutions, and electric vehicles (EVs) provide an alternative means of greener driving. Hence, the share of battery-driven vehicles is expected to rise dramatically. For instance, Canalys, a well-known analysis company, predicts that EVs will account for 48% of passenger cars sales worldwide in 2030 [5].

Lithium-ion batteries (LIBs) have received considerable attention due to their essential role in EVs [6-8]. Most previous studies have investigated the advanced technologies of EV-LIB production and recycling [9, 10], circular economy strategies for EV-LIBs [11, 12], health estimation for LIBs [13, 14], end-of-life management [15, 16] and the carbon footprint of EV-LIBs [17]. However, few studies have explored EV-LIB-related commodities from a trade network perspective, such as in reference to the lithium trade network [18], cobalt trade network [19, 20], LIB critical resource trade network [21], and EV-LIB product trade network [22]. The complicated dependent relationships between upstream and downstream products have not received attention. Figure 1 presents the global EV-LIB supply network (GELSN), which requires further study due to the uneven spatial distribution of raw minerals worldwide and transnational LIB collaborative production.

The GELSN has been threatened by economic fluctuations, political instability and the spread of coronavirus disease 2019 (COVID-19) in recent years. In addition, the intricate trade relationships of individual commodities among countries create vulnerabilities, and the dependencies between upstream and downstream commodities further exaggerate risks in the GELSN. Hence, potential sources of risk in the GELSN must be identified. Although Hu et al. [22] revealed the hidden risks in the global EV-LIB single-layer trade network, the systemic risks of the GELSN have not received sufficient attention. Systemic risk is the risk that a large fraction of a system will collapse because of seemingly minor and local shocks that initially affect only a small part of the system [23]. Due to the complicated connections in the system, the shocks will eventually propagate throughout the entire network, which may be underestimated without close attention to the cascade process. Understanding critical risk sources will help policymakers hedge supply risks and ensure industrial safety. Providing such help motivates us to explore the GELSN due to its significance in supporting a reliable and uninterrupted supply of EV-LIBs. To fill the identified research gaps, this study addresses the complex structural evolution of the GELSN from a multilayer network perspective, and it focuses on critical risk sources from static and dynamic network perspectives.



Note: The key mineral resources in EV-LIBs include nickel, cobalt and lithium. The intermediate components include cathodes, anodes, separators, and electrolytes. The GELSN is a multilayer network model that includes the mineral resource trade network, intermediate component trade network and EV-LIB trade network. The descendant stage depends on the ancestor stage. Dependent relationships are represented by dotted arrows. Notably, there are dependent relationships between the nickel/cobalt/lithium and cathode layers. In the second and third stages, there are dependent relationships between the cathode/anode and EV-LIB layers. To clearly illustrate the multilayer GELSN, the dependent relationships between layers are depicted in the schematic diagram. Each subnetwork includes a single-commodity trade network. Nodes represent countries, and arrows show the trade relationships between countries. The same countries in different subnetworks are connected.

Figure 1. Schematic diagram of the GELSN

The contributions of this study are as follows. (1) An analytical framework is proposed based on the multilayer network model to depict the intricate and heterogeneous GELSN system. This framework takes into account the global trade relationships among countries for major EV-LIB-related commodities and the supply relationships between upstream and downstream countries. The definition overcomes the limitation of the single-layer network model for a certain commodity and of the relationships through the supply chain based on the flows of a certain material element instead of the direct supply relationships. (2) From the perspective of influence, static risk is evaluated for countries and six commodities based on the MultiRank algorithm considering the trade volume, the significance of trade partners and the position of commodities in the supply chain. These three important issues are ignored by previous studies. (3) From the dynamic perspective, risk sources are quantitatively evaluated based on the proposed shock propagation models under two realistic scenarios, and the detailed shock transmission paths through the trade and supply relationships are revealed. This study breaks through limitations stemming from the fact that previous studies have neglected the cross-layer propagation through the supply chain as well as the quantitative analyses in previous studies. The analytical framework and findings can provide support for industry practitioners to comprehend systemic risks and for policymakers in different countries involved to formulate strategies to stimulate stable development with an overall consideration of the whole supply chain and global trade.

The rest of this work is organized as follows. Section 2 reviews previous studies. The data and methods are described in Section 3. Section 4 investigates the key risk countries and commodities from a static perspective. Section 5 reveals the critical risk countries and detailed risk propagation paths from a dynamic perspective. Finally, a discussion and conclusion are provided in Section 6.

2. Literature review

2.1 Material flow analysis and complex networks for EV-LIBs

The main tools used in previous studies on commodities in the GELSN are material flow analysis (MFA) and complex network theory, each of which offers unique advantages. MFA is an effective means of understanding the industrial metabolism of a certain commodity and shows the flow patterns in a region. To date, various MFA studies have been conducted in various regions/countries, such as for nickel [24, 25], cobalt [11, 26] and lithium [27, 28]. MFA has the advantage of revealing the complete transfer processes of a certain material element from raw materials and energy to finished and spent products. Material flows based on the MFA method reveal the input and output of a certain element among different commodities. The core goal of MFA-related studies is to reveal the sources, pathways and destinations of a material element [29]. The connections between different commodities are based on a certain material element instead of the direct supply relationships between upstream and downstream commodities. In addition, many MFA studies focus on a certain region, a few countries or some coarse-grained regions under the limitation of statistical data [30, 31], and detailed analyses of all countries are lacking. Moreover, in MFA studies, the trade activities among countries are used mainly as flows to calculate the distribution of a certain material element among countries. A few studies add only the exports or imports for a region in a certain mineral life cycle [31, 32]. The detailed and complicated trade patterns, such as the indirect trade connections among countries, cannot be explored.

Compared to MFA, complex network theory offers various network models to flexibly reflect the heterogeneous network structure, in which edges can depict different types of multidirectional relationships between nodes instead of the single relationship with regard to a certain material element. In addition, abundant structural metrics and algorithms in complex network theory provide powerful tools to understand second-order or higher-order neighboring relationships, to mine local and global structural patterns, and to model dynamic evolutionary patterns. For instance, the dynamic evolution of the trade network for an individual commodity has been investigated from various perspectives, such as in terms of community structures [18, 33], competitive relationships [34, 35] and backbone structures [22]. Regarding EV-LIB-related commodities, the communities of global lithium trade networks [18], the role of trading countries and the potential trade connections in the cobalt trade dependence network [20] [19] and the dynamic evolution of the EV-LIB trade network [22] have been investigated. Some studies have focused on the supply chain of LIBs. Olivetti et al. [36] analyzed critical metals in the LIB supply chain. Coffin and Horowitz [37] described the structure of the EV battery supply chain and estimated the value added to EV batteries for EVs in the USA. Li et al. [38] proposed an optimization model to maximize profits in the supply chain network for LIBs and analyzed the critical factors of profitability. However, these studies conducted only simple analyses and lacked a systematic perspective with an overall consideration of the trade relationships among countries and the supply relationships among upstream and downstream commodities to investigate the GELSN.

2.2 Risk analysis of trade networks

Two general approaches are used for risk analysis of trade networks: static risk indicators and dynamic risk transmission. Static indicators focus on the characteristics of countries based on two aspects. Exports and imports, as the simplest widely used metrics, measure risk sources based on the influence of their market size. However, the influence of only first-order relationships is considered, and the influence of trade partners and the different levels of significance of commodities in supply chains are ignored. In addition to exports and imports, some indicators have been proposed to evaluate the possibility of emerging trade issues between countries, such as the World Governance Index [39], substitutability index [40], and Herfindahl-Hirschman index [41]. Wu et al. [42] established a criteria system for assessing risks in the EV supply chain and for evaluating risk levels in China, and Helbig et al. [43] proposed a semiquantitative index system to assess the supply risk scores of functional materials in LIB supplies. However, these indicators measure the possibility of risk broadly and cannot focus on specific risk scenarios.

In contrast to static indicators, shock propagation models based on complex network theory not only evaluate the scale of influence under diverse shock scenarios but also intuitively depict the specific dynamic risk transmission paths considering the intricate relationships in networks. In particular, the linear threshold model [44] and cascading failure model [45] are widely used to analyze network vulnerabilities. In recent years, studies have introduced these dynamic models to study EV-LIB-related commodity networks. For instance, Hu et al. [22] revealed the hidden risks involved in the global EV-LIB trade by simulating the proposed shock propagation models in trade networks. Tian et al. [21] simulated a disturbance procedure based on the proposed models for the critical LIB resources. However, neither static indicators nor dynamic shock propagation models consider the dependence between upstream and downstream commodities, leading to an underestimation of the systemic risks in the GELSN.

2.3 Identified gaps for the EV-LIB supply network

Most previous studies have analyzed a certain core mineral resource or EV-LIBs to reveal the industrial metabolism throughout the life cycle or network structural characteristics. Some issues must be explored in depth. First, an analytical framework that comprehensively considers the intricate and heterogeneous trade and supply relationships should be developed. There are two types of relationships in the GELSN: the trade relationships among countries for EV-LIB-related commodities and the direct supply relationships between upstream and downstream commodities for countries. In addition, the trade relationships among countries for commodities have an impact on the supply relationships. Although some MFA-based studies discuss the material flows of a certain element or some elements in the EV-LIB supply chain, the connections are built with regard to a certain material element rather than the direct supply relationships between upstream and downstream commodities. Additionally, despite the rich tools in complex network theory, studies that adopt this methodology mainly focus on a certain commodity trade network by constructing a single-layer network model, which means that a systematic consideration of the GELSN with some single-layer trade networks and the cross-layer supply connections between different commodities is lacking. Second, static risk evaluation based on the centrality of significant countries and commodities should be conducted under a comprehensive understanding of the complicated relationships between countries, commodities and the supply chain. Previous studies have assessed the importance of countries mainly based on the volume of exports or imports or based on the structural characteristics of a single-layer trade network. In fact, the significance of countries is influenced not only by the volume of exports/imports but also by the significance of their trade partners and of the commodities in the supply chains. Meanwhile, commodities have different positions in the supply chain, and the significance of commodities is affected by the significance of the active countries in a commodity's trade network. Third, dynamic risk evaluation should be conducted from a systemic and multilayer perspective. Previous studies have mainly focused on the risk transmission in a single-layer trade network, ignoring the shock propagation from the single-layer trade network of upstream commodities to downstream commodities, which underestimates risks in the supply network.

To fill this gap, first, this study proposes an analytical framework by using a multilayer network model that represents the trade relationships between countries for each commodity in the supply chain and the direct supply relationships between upstream and downstream commodities. Second, critical risk sources are identified based on the static centrality indicator using the MultiRank algorithm while comprehensively considering a country's trade structure and the significance of commodities in the supply chain. Third, critical risk sources are assessed with the proposed dynamic shock propagation models under two realistic scenarios, i.e., supply restrictions on a specific commodity and blocked export channels. The identified critical risk sources in the GELSN can provide policymakers with insights to adjust trade strategies and ensure industrial safety.

3. Data and methods

3.1 Data description and network topology

There are a large number of commodities in the GELSN. Due to the complicated supply relationships of upstream and downstream commodities and the limitation of public datasets, the GELSN is simplified in this study as a system with six kinds of commodities. The commodities considered in the GELSN include mineral resources (nickel, cobalt and lithium), intermediate components (cathode and anode materials) and finished products (EV-LIBs). All records of trade between countries for these commodities from 1990 to 2020 are retrieved from the United Nations Comtrade database. The specific commodities considered and data preprocessing methods used are illustrated in Appendix A1.

Based on complex network theory, this study uses the multilayer network model to construct the annual GELSN from 1990 to 2020. Figure 1 shows that the GELSN consists of six single-layer networks, labeled L_1 to L_6. For instance, the global nickel trade network is constructed as single-layer network $G^{[t,\mathrm{L}_1]} = (V^{[t,\mathrm{L}_1]}, E^{[t,\mathrm{L}_1]}, \mathbf{W}^{[t,\mathrm{L}_1]})$, in which the set of nodes $V^{[t,\mathrm{L}_1]}$ represents countries, the trade relationships between countries are represented by $E^{[t,\mathrm{L}_1]} = \{(i,j) \mid i,j \in V^{[t,\mathrm{L}_1]}\}$, and t represents the year. Weight matrix $\mathbf{W}^{[t,\mathrm{L}_1]} = \{w_{ij}^{[t,\mathrm{L}_1]} \mid (i,j) \in E^{[t,\mathrm{L}_1]}\}$ represents the trade value between countries. The signal adjacency matrix is $\mathbf{A}^{[t,\mathrm{L}_1]} = \{a_{ij}^{[t]} \mid i,j \in V^{[t,\mathrm{L}_1]}\}$, where $a_{ij}^{[t,\mathrm{L}_1]} = 1$ if $(i,j) \in E^{[t,\mathrm{L}_1]}$ and $a_{ij}^{[t,\mathrm{L}_1]} = 0$ if $(i,j) \notin E^{[t,\mathrm{L}_1]}$. Similar to the global single-layer nickel trade network $G^{[t,\mathrm{L}_1]}$, the global single-layer cobalt/lithium/…/EV-LIB trade networks are defined as $G^{[t,\mathrm{L}_2]} / G^{[t,\mathrm{L}_3]} / \ldots / G^{[t,\mathrm{L}_6]}$.

On the basis of the six single-layer trade networks, the GELSN is built as $MG^{[t]} = (SG^{[t]}, CE^{[t]})$, where $SG^{[t]}$ denotes the set of single-layer trade networks $SG^{[t]} = \{G^{[t,l]} \mid l \in \{\mathrm{L}_1, \mathrm{L}_2, \ldots \mathrm{L}_6\}\}$ in year t and $CE^{[t]}$ is the set of links between the same nodes in different single-layer trade networks. It is named the cross layer, and it consists of two components: intrastage edges and interstage edges. In the same stage, the same nodes in different single-layer networks are connected by undirected intrastage edges, which are shown as orange dotted links. Specifically, there are intrastage edges in the first stage (raw mineral sources) between the same nodes in the single-layer trade network of nickel, cobalt or lithium. The cross layers are the abstraction of the supply chain for the domestic production process. The intrastage edges reflect the association relationships between commodities in the same stage, and the interstage edges represent the supply relationships between upstream and downstream commodities. Due to the sequential order of the four stages in the GELSN, the single-layer networks between two successive stages have dependent relationships, which are shown as the green edges representing directed interstage links in Figure 1. In particular, there are interstage links from nickel/cobalt/lithium to the cathode single-layer trade network and from cathode/anode materials to the EV-LIB single-layer trade network. Therefore, given the abstraction of the GELSN in the real world, the multilayer model represents the supply relationships among countries for each critical commodity in international trade as well as the supply relationships among the upstream and downstream critical commodities in each country's EV-LIBs domestic production process. The domestic production of each commodity is not explicitly reflected in the multilayer model. Rather, it is reflected by the country's anti-risk capacity set as the threshold parameter in the proposed dynamic shock propagation models. The detailed definition is illustrated in Section 3.3.

To calculate the structural characteristics of the GELSN, the multilayer network is simplified as a multiplex network $PG^{[t]}=(SG^{[t]},PE^{[t]})$, where $PE^{[t]}$ is the set of undirected edges between the same nodes in different single-layer networks. To review the synopsis of the GELSN, the topological characteristics are analyzed from two perspectives, namely, based on basic metrics of a single-layer network and the relationships between single-layer networks. Because of the widespread use of these indicators, detailed definitions are provided in Appendix A2.

3.2 Static centrality of the multiplex supply network

Network centrality is an important static indicator that reveals the critical risk sources in a network. Thus, the MultiRank algorithm [46] is introduced in this study to evaluate the centrality of countries and commodities to reveal critical risk sources in the GELSN. Specifically, for a multiplex network PG with N nodes and M layers, the centrality of node i is defined as p_i, and the influence of layer l is defined as $z^{[l]}$.

The algorithm is based on two assumptions. First, a node will have more centrality when it receives links from highly influential layers and from the identified central nodes. Second, a given layer has more influence when nodes of high centrality are active in the layer. The MultiRank algorithm transfers a multiplex network as a colored network and a weighted and directed bipartite network [47, 48]. The definitions of the colored network and bipartite network are shown in Appendix A3.

The algorithm of centrality in the single-layer network based on the random walk PageRank [49] is extended to the multiplex network. The centrality of node i, represented as p_i, and the influence of layer l are calculated based on the following equations:

$$p_i = d\sum_{j=1}^{N} \frac{g_{ji}}{\mu_j} p_j + \beta\eta_i , \tag{1}$$

$$z^{[l]} = \frac{1}{\omega}\left[W^{[l]}\right]^{a}\left[\sum_{i=1}^{N} B_{li}^{in}(p_i)^{s\gamma}\right]^{s} , \tag{2}$$

where $g_{ij} = \sum_{l=1}^{M} w_{ij}^{[l]} z^{[l]}$, $\mu_j = \max(1, \sum_{i=1}^{N} g_{ji})$, and η_i is the Heaviside function, which is calculated by $\eta_i = \theta\left(\sum_{j=1}^{N}[g_{ij} + g_{ji}]\right)$. $\beta = \frac{1}{\sum_{i=1}^{N}\eta_i}\sum_{j=1}^{N}\left[1 - d\theta\left(\sum_{i=1}^{N} g_{ji}\right)\right]p_j$. d is the damping factor, and ω is a normalization constant. a, s and γ are parameters used to define the strength between the influence of layers and the centrality of nodes under the two assumptions. The MultiRank algorithm is calculated based on the power iteration method, and the detailed settings of the parameters are shown in Appendix A3.

3.3 Single-layer network shock propagation model

In this subsection, dynamic shock propagation models are proposed to describe the detailed risk transmission paths and to reveal critical risk sources in the single-layer trade networks. For a single-layer trade network, the shock propagation model describes supply restrictions on a specific commodity. In a previous study, Hu et al. [22] proposed a trade network risk transmission model based on a linear threshold model [44] to depict risk transmission in the GELSN. This study uses this proposed model to assess the risk caused by supply restrictions on a certain commodity in different countries.

In single-layer network $G^{[t,l]}$ for layer $l \in \{\mathrm{L}_1, \mathrm{L}_2, \ldots, \mathrm{L}_6\}$ in year t, nodes will have two states under the shock of a supply shortage caused by a given seed node, namely, the normal state and avalanched state. In the initial step ($it = 1$), all the exports of a given seed node i are reduced for a certain reason. That is, the weight of the edge in iteration step $w_{ij}^{[t,l]}(it=1)$ is set to 0 for $(i,j) \in E^{[t,l]}$. Notably, the seed node remains in a normal state in this study. In the second step ($it = 2$), due to the export reduction in the seed node, export partners must face import shortages. When the import shortages exceed the threshold, the normal state of the export partners will transfer to the avalanched state. In other words, country j with $(i,j) \in E^{[t,l]}$ is avalanched when $\sum_{(k,j)\in E^{[t,l]}} w_{kj}^{[t,l]}(it=1) < (1-r)s_j^{[t,l]}(in)$, where $s_j^{[t,l]}(in)$ is the original in-strength of node j in single-layer network $G^{[t,l]}$ and r is the threshold of anti-risk capacity, ranging from 0 to 1. Notably, the volume of domestic production for a certain commodity reflects the ability to withstand the shock of an import reduction. Different values of the threshold parameter indicate a diverse volume of domestic production to cover the import deficit. Due to limitations in the statistical data on the domestic production of each commodity, domestic production, reflected by anti-risk capacity, is set to be proportional to each country's imports. For each country, the same proportion setting may lead to uncertainty in the results, which is discussed in Appendix A6. Then, the shock is propagated through the avalanched nodes to their export partners. That is, the second step is repeated. When the number of avalanched nodes remains unchanged, the iteration process stops. The iteration count indicates how quickly the shock propagates through single-layer network $G^{[t,l]}$.

Based on the proposed shock propagation model, the number of avalanched nodes and the iteration count caused by a given seed node in each layer network are obtained. That is, in single-layer network $G^{[t,l]}$, the export reduction of node i leads to $as_i^{[t,l]}$ avalanched nodes in $is_i^{[t,l]}$ iterations. To measure the fragility of a single-layer network, indicators are defined as the average number of avalanched nodes and iterations weighted by the ratio of exports to total exports in this single-layer network. The specific definitions are represented by the following equations:

$$as^{[t,l]}=\frac{s_i^{[t,l]}(out)as_i^{[t,l]}}{\sum_{j\in V^{[t,l]}}s_j^{[t,l]}(out)},\quad is^{[t,l]}=\frac{s_i^{[t,l]}(out)is_i^{[t,l]}}{\sum_{j\in V^{[t,l]}}s_j^{[t,l]}(out)}, \tag{3}$$

where $s_i^{[t,l]}(out)$ is the out-strength of node i in single-layer network $G^{[t,l]}$ and $l\in\{L_1,L_2,\ldots,L_6\}$. Single-layer network $G^{[t,l]}$ will be more fragile if it has a higher $as^{[t,l]}$. A lower $is^{[t,l]}$ indicates that the shock in single-layer network $G^{[t,l]}$ propagates more quickly.

3.4 Multilayer network shock propagation model

For the multilayer trade network, dynamic shock propagation models are developed for two realistic scenarios: supply restrictions on a specific commodity and blocked export channels. Scenario 1 depicts supply restrictions on a specific commodity in a certain country. As shown in Figure 1, the avalanched nodes of a single-layer trade network in the prestage will lead to the same nodes being avalanched in the next-stage single-layer trade network. In the GELSN, the single-layer trade networks of mineral resources, including nickel $G^{[t,L_1]}$, cobalt $G^{[t,L_2]}$ and lithium $G^{[t,L_3]}$, are upstream of cathode trade network $G^{[t,L_4]}$. EV-LIB trade network $G^{[t,L_6]}$ is downstream of cathode trade network $G^{[t,L_4]}$ and anode trade network $G^{[t,L_5]}$.

Therefore, in the multilayer network shock propagation model, supply restrictions on a specific commodity trade network $G^{[t,l_1]}$ caused by seed node i will spread in the single-layer network first, as illustrated in Subsection 3.3. Then, the avalanched nodes in $G^{[t,l_1]}$, defined as the node set $VA_i^{[t,l_1]}$, will lead to the same nodes being avalanched in $G^{[t,l_2]}$, where $G^{[t,l_2]}$ is the downstream network of $G^{[t,l_1]}$. The number of nodes in $VA_i^{[t,l_1]}$ is $am_i^{[t,l_1]}$. These avalanched nodes will propagate shocks in $G^{[t,l_2]}$. The set of avalanched nodes in $G^{[t,l_2]}$ is defined as $VA_i^{[t,l_2]}$, and $am_i^{[t,l_2]}=|VA_i^{[t,l_2]}|$. The shock will spread further through $VA_i^{[t,l_2]}$ in $G^{[t,l_2]}$ to downstream network $G^{[t,l_3]}$. For instance, a shock occurring in the single-layer trade network of a mineral resource will lead to propagation in the GELSN, as shown in Figure 2. The results show that a shock triggered by country i in the mineral resource trade network is propagated in the multilayer supply network and ultimately leads to all countries in the finished product trade being avalanched.

Notably, the threshold of nodes with shock resistance in different single-layer networks varies. The threshold in network $G^{[t,l]}$ is defined as $r^{[t,l]}$, where $l\in\{L_1,L_2,\ldots,L_6\}$. In the GELSN, the shock will propagate in five scenarios: $(\mathrm{L}_1 \rightarrow \mathrm{L}_4 \rightarrow \mathrm{L}_6)$, $(\mathrm{L}_2 \rightarrow \mathrm{L}_4 \rightarrow \mathrm{L}_6)$, $(\mathrm{L}_3 \rightarrow \mathrm{L}_4 \rightarrow \mathrm{L}_6)$, $(\mathrm{L}_4 \rightarrow \mathrm{L}_6)$ and $(\mathrm{L}_5 \rightarrow \mathrm{L}_6)$. To evaluate the impacts of nodes with supply restrictions on a specific commodity, a group of indicators is calculated as the average ratio of avalanched nodes to the total number of nodes in each single-layer network under a scenario with different thresholds. For scenario $(l_1 \rightarrow l_2 \rightarrow l_3)$, the impacts of node i with supply restrictions on $G^{[t,l_1]}$ in l_1 are calculated as

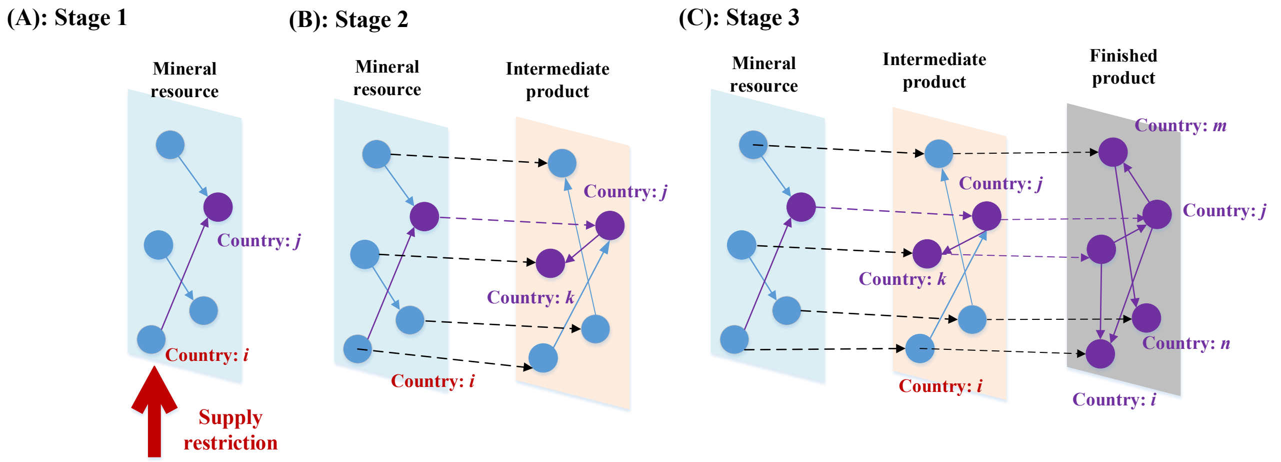
$$\overline{am_i^{[t,l_1]}} = \frac{1}{3N^{[t,l_1]}} \sum\nolimits_{r^{[t,l_1]}\in\{0.1,0.5,0.9\}} am_i^{[t,l_1]}(r^{[t,l_1]}), \tag{4}$$

where $am_i^{[t,l_1]}(r^{[t,l_1]})$ is a function of threshold setting $r^{[t,l_1]}$, measuring the number of avalanched nodes in $G^{[t,l_1]}$ with threshold setting $r^{[t,l_1]}$, and $N^{[t,l_1]}$ is the number of nodes in $G^{[t,l_1]}$. Similarly, the impacts on $G^{[t,l_2]}$ and $G^{[t,l_3]}$ are calculated as:

$$\overline{am_i^{[t,l_2]}} = \frac{1}{9N^{[t,l_2]}} \sum\nolimits_{r^{[t,l_1]},r^{[t,l_2]}\in\{0.1,0.5,0.9\}} am_i^{[t,l_2]}(r^{[t,l_1]},r^{[t,l_2]}), \tag{5}$$

$$\overline{am_i^{[t,l_3]}} = \frac{1}{27N^{[t,l_3]}} \sum\nolimits_{r^{[t,l_1]},r^{[t,l_2]},r^{[t,l_3]}\in\{0.1,0.5,0.9\}} am_i^{[t,l_2]}(r^{[t,l_1]},r^{[t,l_2]},r^{[t,l_3]}), \tag{6}$$

where $am_i^{[t,l_2]}(r^{[t,l_1]},r^{[t,l_2]})\ /\ am_i^{[t,l_2]}(r^{[t,l_1]},r^{[t,l_2]},r^{[t,l_3]})$, as a function of the threshold setting ($r^{[t,l_1]}$, $r^{[t,l_2]}$)/($r^{[t,l_1]}$, $r^{[t,l_2]}$, $r^{[t,l_3]}$), indicates the number of avalanched nodes in $G^{[t,l_2]}/G^{[t,l_3]}$.



Note: (A) Country i restricts exports in the single-layer trade network of mineral resource $G^{[t,l_1]}$. This restriction leads to node j being avalanched, which is shown in purple. (B) Due to the interdependent relationships between mineral resources and intermediate products, the shock in $G^{[t,l_1]}$ spreads to the single-layer trade network of intermediate component $G^{[t,l_2]}$. That is, avalanched node j in $G^{[t,l_1]}$ will lead to node j in $G^{[t,l_2]}$ being avalanched. In single-layer network $G^{[t,l_2]}$, node k is shocked and transfers from the normal state to the avalanched state due to avalanched node j. (C) The shocks are further propagated from the intermediate component to the finished product through the interdependent relationships. In the single-layer trade network for finished product $G^{[t,l_3]}$, countries m, n and i are avalanched because of countries j and k.

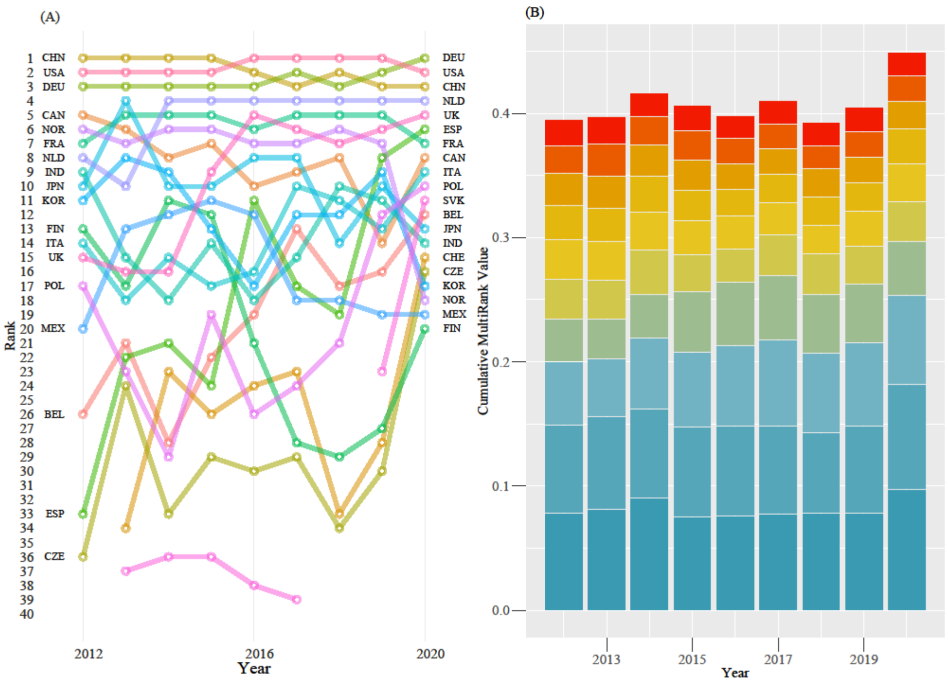
Figure 2. Cascading failure in node disruption for a specific commodity

Scenario 2 depicts the extreme event of supply restrictions on all commodities in a certain country, i.e., export channels are completely blocked. Different from scenario 1, the supply restriction shocks of node i in $G^{[t,\mathrm{L}_1]}$, $G^{[t,\mathrm{L}_2]}$ and the other four single-layer networks are propagated simultaneously in the first stage. Then, the avalanched nodes in $G^{[t,\mathrm{L}_1]}$, namely, $VA_i^{[t,\mathrm{L}_1]}$, lead to the same nodes in $G^{[t,\mathrm{L}_4]}$ being avalanched. Similarly, the avalanched nodes in $G^{[t,\mathrm{L}_2]}$ / $G^{[t,\mathrm{L}_3]}$ also propagate shocks to $G^{[t,\mathrm{L}_4]}$. Notably, the union set of the nodes avalanched in $G^{[t,\mathrm{L}_4]}$ in the first stage and the avalanched nodes in $G^{[t,\mathrm{L}_4]}$ caused by $G^{[t,\mathrm{L}_1]}$, $G^{[t,\mathrm{L}_2]}$ and $G^{[t,\mathrm{L}_3]}$ jointly propagate shock in $G^{[t,\mathrm{L}_4]}$ and lead to avalanched nodes $VA_i^{[t,\mathrm{L}_4]}$. The avalanched nodes in EV-LIB trade network $G^{[t,\mathrm{L}_6]}$ are caused by the joint effects of avalanched nodes $VA_i^{[t,\mathrm{L}_4]}$ and $VA_i^{[t,\mathrm{L}_5]}$, and the nodes avalanched in $G^{[t,\mathrm{L}_6]}$ in the first stage. Similar to the definition of impacts in Equation (3), the impacts of node i on network $G^{[t,l]}$ are calculated as the average ratio of avalanched nodes to the total number of nodes in $G^{[t,l]}$ with all potential settings of thresholds in the six single-layer trade networks.

4. Static analysis results

A synopsis of the GELSN is provided in terms of topological characteristics in Subsection 3.1, and the detailed results are presented in Appendix A4. Overall, the GELSN grows steadily. The import competition and export monopolization of EV-LIBs are higher than those of other commodities. From 1990 to 2020, an increasing amount of trade value for each commodity in the GELSN was controlled by a few countries. Specifically, the heterogeneity of the EV-LIB trade is higher than that of most other commodities. The results show a stronger association between the single-layer network of intermediate components (cathode and anode) and that of finished products (EV-LIBs). Therefore, it is assumed that these trade markets will be highly synchronized under shocks.

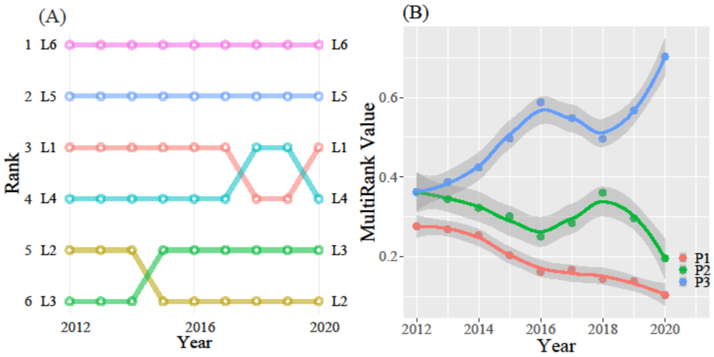
As illustrated in Subsection 3.2, the static centrality of countries and the influence of different layers in the GELSN are measured simultaneously by the MultiRank algorithm. Figure 3(A) shows the variation in the rankings of the top 20 countries in terms of centrality in 2020. From 2012 to 2020, China, the USA and Germany remained the most important countries in the GELSN. Notably, although South Korea and Japan were ranked second and third in exports of EV-LIBs from 2012 to 2020, they do not occupy the corresponding central positions in the GELSN. The main reason is that South Korea and Japan do not have sufficient impacts on mineral resources. Except for China, the USA and Germany, the ranks of some countries change considerably with the development of the GELSN. Most countries with central positions in the GELSN are located in Europe, and the impacts of these European countries increase. In particular, sharp improvements are observed in the rankings of Spain, the UK, Slovakia, Belgium, and Czechia. In contrast to those of European countries, the rankings of core Asian countries, such as Japan and South Korea, show a downward fluctuating trend. Figure 3(B) reflects the cumulative significance of the top 10 countries. The results show that the sum of centrality of the top 10 countries has a fluctuating upward trend and reaches a maximum value of approximately 0.5. These results reflect the heterogeneity of the GELSN, which is in line with the characteristics of the trade networks of a single commodity shown in Appendix A4.



Note: (A) Variation in the rankings of the top 20 countries in terms of centrality in 2020. (B) Cumulative distribution of the centrality of the top 10 countries from 2012 to 2020. Blocks shaded in blue to red represent the top 10 countries sorted by centrality. The heights of the colored blocks indicate the centrality of countries measured by the MultiRank algorithm.

Figure 3. Changes in core countries with high centrality in the GELSN

Figure 4 shows the changes in the influence of layers in the GELSN. Notably, the layers of EV-LIBs and anode materials are ranked first and second, respectively, in Figure 4(A). The next layers with a strong impact on the supply network are the nickel and cathode layers. Moreover, the lithium layer climbed one spot from 2012 to 2020. In 2020, the cobalt layer had the weakest influence on the GELSN. To explore the changes in influence in each stage from a fine-grained perspective, the sum of the influence of layers in the same stage is calculated. Figure 4(B) depicts the influence of layers on mineral resources, intermediate components, and finished products. In 2012, the layer of intermediate components had the greatest impact on the supply network, and there was little variation in the influence of layers on mineral resources, intermediate components, and finished products in 2012. In addition, the results show that the EV-LIB layer had a growing influence, reaching a peak in 2020 of approximately 0.70, which is greater than that of the other layers. In contrast, the effects of the mineral resource and intermediate component layers decline to the lowest values of 0.10 and 0.20, respectively. The variation trends shown in Figure 4(B) demonstrate that countries developed high EV-LIB technologies and reduced their dependence on mineral resources with the development of the EV-LIB industry from 2012 to 2020. In particular, the core countries with high centrality are more active in the EV-LIB trade network. Thus, the layer of EV-LIBs has a great impact on the GELSN.



Note: (A) Variation in the rankings of the six layers measured in terms of influence from 2012 to 2020. (B) Variation in the influence of the three stages from 2012 to 2020. The single-layer trade networks for nickel, cobalt, lithium, cathodes, anodes and EV-LIBs are represented as L1, L2, L3, L4, L5 and L6, respectively. The stages of mineral resources, intermediate components, and finished products are labeled P1, P2, and P3, respectively. In particular, the influence of mineral resources is calculated as the sum of the influence of the nickel, cobalt and lithium layers. Similarly, the influence of intermediate components is defined as the sum of the influence of the cathode and anode layers.

Figure 4. Changes in the influence of layers in the GELSN

5. Dynamic analysis results

As defined in Subsections 3.3 and 3.4, the dynamic shock propagation models are simulated based on the GELSN for 2020. In this section, for the single-layer networks, the parameter describing the anti-risk capacity of countries in each single-layer trade network varies from 0.1 to 0.9 in increments of 0.1. For the multilayer network, the threshold parameter varies from 0.1 to 0.9 in increments of 0.4.

5.1 Shock propagation in a single-layer trade network

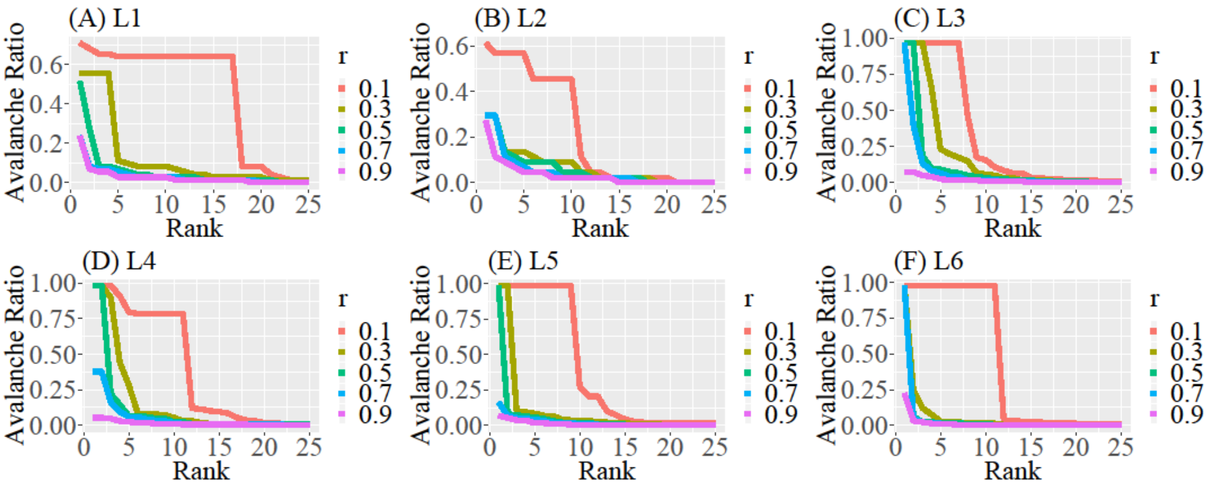
Table 1 shows the 5 countries with the greatest influence on the single-layer trade networks when the threshold parameter is set to 0.1. The impacts of supply restrictions caused by different risk sources are shown in Figure 5. The results show that the countries with the greatest impacts on the single-layer networks of the nickel, cobalt and lithium trade are abundant in the corresponding mineral resources and are mainly located in Africa and South America. These countries include Zimbabwe, South Africa, Zambia and Chile. In regard to the trade networks of cathodes/anodes and EV-LIBs, highly developed industrialized countries, such as Japan, South Korea and China, have prominent effects.

Table 1. Top 5 countries in terms of avalanche ratios with the threshold set to 0.1

	L1		L2		L3	
Rank	Country	Avalanche ratio	Country	Avalanche ratio	Country	Avalanche ratio
1	Zimbabwe	0.71	Zambia	0.61	Chile	0.97
2	South Africa	0.68	China	0.57	Belgium	0.97
3	Malaysia	0.65	South Africa	0.57	Germany	0.97
4	New Caledonia	0.65	Congo	0.57	Netherlands	0.97
5	China	0.64	South Korea	0.57	USA	0.97

	L4		L5		L6	
Rank	Country	Avalanche ratio	Country	Avalanche ratio	Country	Avalanche ratio
1	Japan	0.98	China	0.98	China	0.98
2	South Korea	0.98	Japan	0.98	South Korea	0.98
3	China	0.98	Germany	0.98	Japan	0.98
4	USA	0.91	South Korea	0.98	Germany	0.98
5	Poland	0.80	USA/France/Spain	0.98	Malaysia	0.98

Note: Countries are ranked in descending order of avalanche ratios and ascending iteration counts.



Note: (A) The nickel layer is labeled L1. (B) The cobalt layer is labeled L2. (C) The lithium layer is labeled L3. (D) The cathode layer is labeled L4. (E) The anode layer is labeled L5. (F) The EV-LIB layer is labeled L6. Countries that are risk sources are ranked by their impacts in descending order. The x-axis represents the ranking of risk sources, and the y-axis denotes the ratio of avalanched countries led by risk sources to the total number of countries in the given layer.

Figure 5. Impacts of supply restrictions in single-layer trade networks

Figure 5 shows that a few risk sources will lead to avalanching in most countries. For example, with the threshold parameter set to 0.1, more than 50% of countries in the cobalt layer (L2) with be avalanched under the shocks caused by the top five countries: Zambia, China, South Africa, Congo, and South Korea. In addition, the distribution of avalanche ratios caused by different sources is uneven. For instance, risk sources with rankings below 12th place will lead to fewer than 13% of countries avalanching in the cathode layer (L4) when the threshold parameter is set to 0.1. Comparing the impacts of supply restrictions, this study finds that the fragility of the six single-layer networks shows varied sensitivity to the threshold parameter settings. These six layers have three different patterns: (1) The avalanche ratio of layers caused by the top five risk sources in nickel minerals with different threshold parameters shows a step-like decline. These layers show moderate sensitivity to the threshold parameter. (2) When the threshold parameter increases from 0.1 to 0.3, the avalanche ratio of layers caused by the top five risk sources in cobalt minerals declines dramatically. The avalanche ratio remains stable when the parameter increases from 0.3 to 0.9. These layers are more sensitive to a low threshold. (3) The avalanche ratio of layers for lithium, cathodes, anodes and EV-LIBs remains stable as the threshold parameter increases from 0.1 to 0.5 but decreases dramatically when the threshold parameter is greater than 0.5. These layers are more sensitive to a high threshold.

Therefore, improving the anti-risk capacity of countries at a low level can enhance the robustness of the single-layer trade network of cobalt minerals more than in the other five single-layer trade networks. In addition, reducing the anti-risk capacity of countries at a high level will lead to a significant weakening of the robustness of the lithium, cathode, anode, and EV-LIB trade networks. Compared to the anti-risk capacity of the countries involved in the other layers, it is urgently necessary to strengthen the anti-risk capacity of the countries involved in the lithium, cathode, anode, and EV-LIB layers.

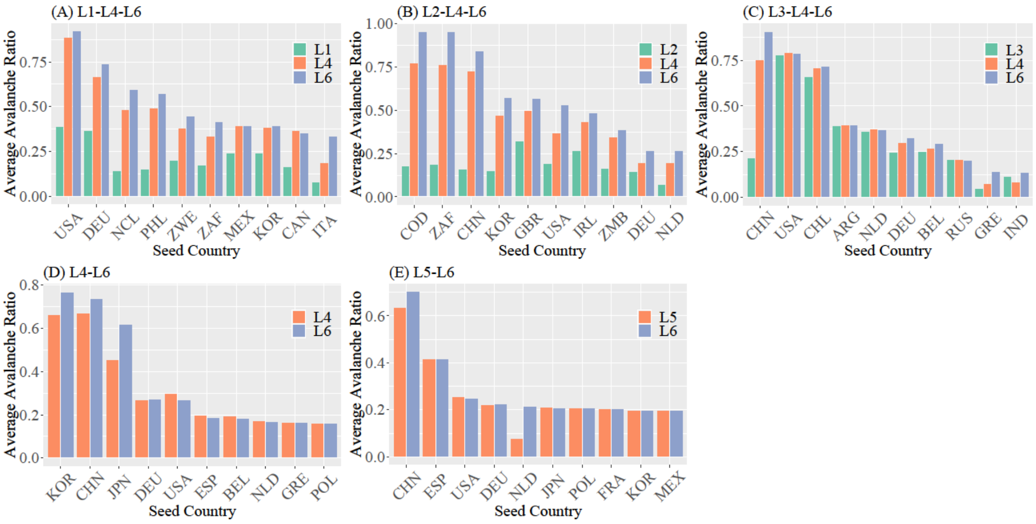
The avalanche size of shocks caused by a certain country in the six single-layer trade networks is evaluated under different settings of the threshold parameters, as shown in Figure 5. Based on the avalanche size caused by a certain country, the fragility of each layer is calculated as the average avalanche size of all countries weighted by the country's exports, as illustrated in Appendix A5. The results show that the cathode layer has the greatest vulnerability, followed by the anode layer and EV-LIB layer. In addition, the findings indicate different sensitivities to the threshold parameter in the layers, which is consistent with the three different patterns obtained from Figure 5.

5.2 Shock propagation in the multilayer supply network

In the GELSN, shock propagation for a single commodity follows five types of paths: (nickel – cathode – EV-LIBs), (cobalt – cathode – EV-LIBs), (lithium – cathode – EV-LIBs), (cathode – EV-LIBs), and (anode – EV-LIBs). Specifically, for a given country, supply restrictions on nickel will cause shock propagation in the nickel layer trade network first. Then, the shocks will spread to the cathode layer because of the precedence relationship between the nickel layer and cathode layer. Finally, the EV-LIB layer will be affected by the avalanched nodes in the cathode layer. This case is represented as the path (nickel – cathode – EV-LIBs). Under this scenario, for a given path, the impacts of shocks triggered by countries are calculated by the average avalanche ratio with different settings of the threshold parameters of single-layer networks, as represented by Equations (4)-(6) in Subsection 3.4. The impacts of shocks triggered by the top ten countries in different paths are shown in Figure 6.

Figure 6(A) represents the impacts of the top ten risk sources in the path (nickel – cathode – EV-LIBs). The results show that supply restrictions on nickel in the USA will lead to more than 38% of countries avalanching in the nickel layer and further trigger 88% and 92% of countries avalanching in the cathode layer and EV-LIB layer, respectively. In addition to the USA, New Caledonia, the Philippines and Zimbabwe, which had the top rankings in terms of nickel exports in 2020, will lead to many countries avalanching in the EV-LIB trade network layer. However, this result does not mean that countries with significant nickel exports have strong impacts on the GELSN. For instance, Indonesia, which has the sixth largest scale of nickel exports, is ranked 23rd (1.3% of countries avalanched in the EV-LIB trade). South Korea leads to the sixth largest avalanche size in the EV-LIB trade but ranks 20th in terms of nickel exports. Therefore, it is worth noting that traditional methods do not consider the intricate relationships between layers in the supply network, which probably ignores some hidden risks and misjudges the impacts of some risk sources.

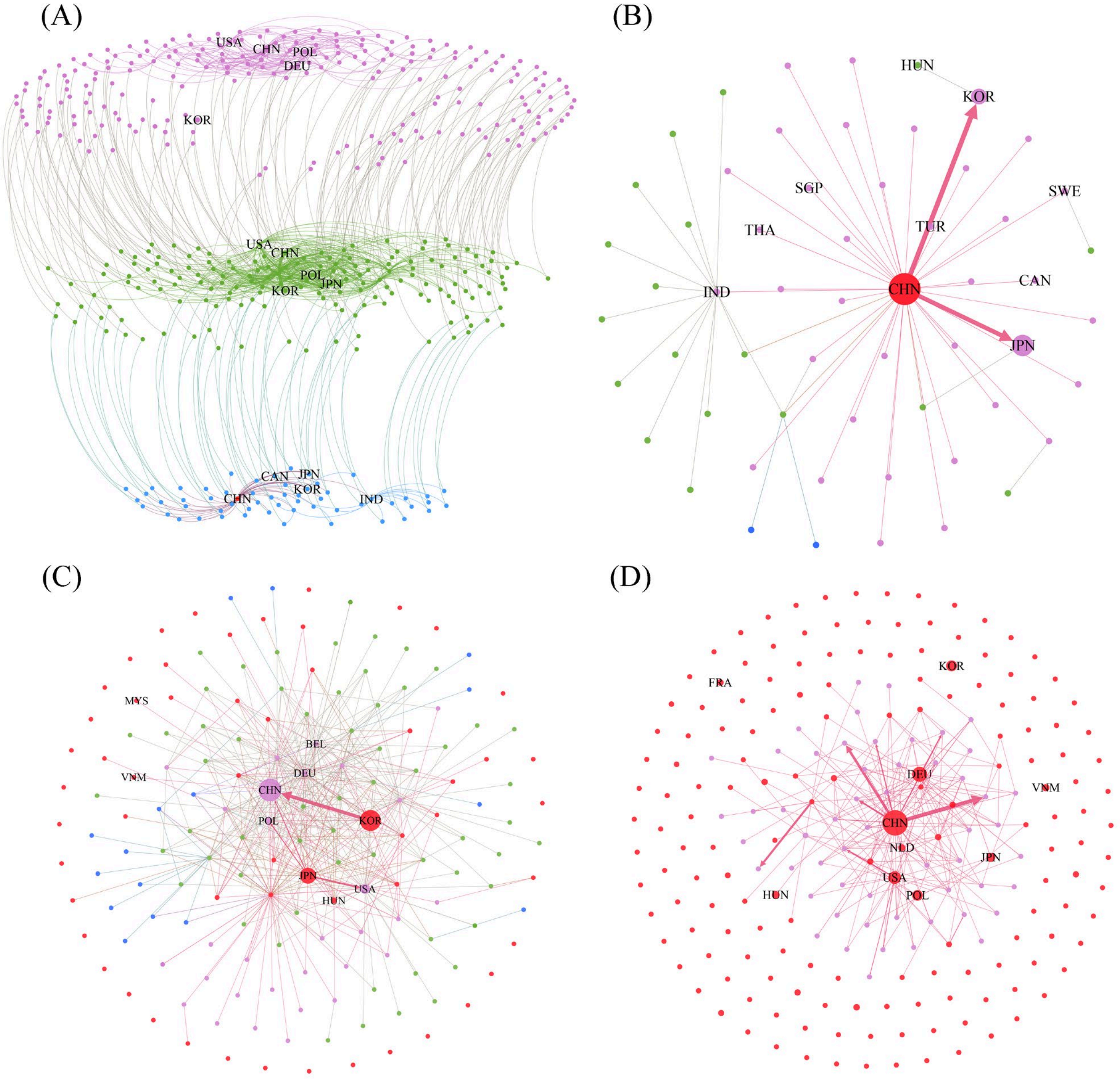
In addition, the expansion of the avalanche ratio from the mineral resource layer to the cathode layer is obviously greater than that from the cathode layer to the EV-LIB layer, as illustrated in Figure 6(A-C). The main reason is the strong structural correlation between the layers of intermediate components and the layer of finished products, as discussed in Appendix A4. Shocks triggered in the lithium layer are slightly greater than those triggered in the nickel and cobalt layers. Figure 6(D) shows that the increase in avalanche size from the lithium layer to the cathode layer is small, similar to that from the cathode layer to the EV-LIB layer. The difference is assumed to be the result of a stronger association between the lithium layer and cathode layer than that between the layers of other mineral resources and the cathode layer, as discussed in Section 4. Notably, China has the greatest impacts on the EV-LIB trade network when restricting lithium supply, which leads to a small range of avalanche sizes in the lithium layer, diverging from the top nine countries in Figure 6(D). However, China’s supply restrictions on cathodes and anodes lead to more than 60% of the countries involved avalanching in the intermediate component and EV-LIB product layers. In addition, Asian countries, including South Korea, China, and Japan, have greater impacts on the cathode layer than the North American and European countries, as shown in Figure 6(E), and further lead to a large avalanche size in the finished product layer.



Note: In the path (L1-L4-L6), countries are sorted by the average avalanche ratio in the EV-LIB layer (L7), cathode layer (L5) and nickel layer (L1) in order of priority. Similarly, the country ranking lists are obtained for the other four paths. The layers of the nickel, cobalt, lithium, cathode, anode and EV-LIB trade networks are represented as L1, L2, L3, L4, L5 and L6, respectively.

Figure 6. Impacts of shocks triggered by the top ten countries in terms of a specific commodity following five paths

To reveal how the shocks triggered by a given risk source in a single-layer trade network propagate in the multilayer supply network, this study takes China's supply restrictions in the lithium trade network as an example to show the risk transmission paths in the multilayer network. In this case, the threshold parameters of the lithium trade network, cathode trade network and EV-LIB trade network are set to 0.1. The transmission paths are shown in Figure 7. The results show that China's supply restrictions on lithium lead to a few countries in the lithium trade avalanching and to substantial impacts on the cathode and EV-LIB trade, as shown in Figure 7(A). The obvious expansion of avalanche size in different layers is thought to be the result of some core countries, such as South Korea, Japan and Hungary, avalanching in the first stage, as shown in Figure 7(B). South Korea, Japan and Hungary have crucial impacts on the avalanches of China, the USA, Germany, and Poland in the cathode trade network and EV-LIB trade network, as depicted in Figure 7(C-D). These avalanched countries further affect other countries in the cathode trade network. Therefore, it is noteworthy that some core countries avalanched upstream of the GELSN will have a great impact on finished products despite having a weak influence upstream. In addition, the results show that few countries have a means of staying safe in the face of shocks in the globalization of trade. Due to the intricate dependent relationships of the supply chain, China's supply restrictions on lithium will lead to a breakdown of the cathode and EV-LIB trade. Therefore, it is crucial for countries to make concerted collaborative efforts to promote normal cooperation in the context of globalization.



Note: (A) Schema of shock propagation in the GELSN. The risk source, China, is shown in red in the layer of the lithium trade network. The three layers of the lithium trade network, cathode trade network and EV-LIB trade network are shown in blue, green and purple, respectively. The top five countries ordered by the trade value in each single layer are labeled with the three-digit country code. (B), (C) and (D) show shock propagation paths in the layers of the lithium trade network, cathode trade network and EV-LIB trade network, respectively. The size of the nodes is determined by the node strength in the given single-layer network. The top ten countries ordered by the trade value are labeled by their names. Nodes are colored red, purple, green, and blue in accordance with the avalanche sequence.

Figure 7. Risk transmission paths of China's supply restrictions on lithium mineral resources

Extreme events such as COVID-19 are likely to lead to comprehensive supply restrictions on all commodities in a certain country. Therefore, as a nonnegligible scenario, shock propagation is modeled as described in Subsection 3.4. Under this scenario, the exports of all commodities in the GELSN to a given country are restricted. The shocks will simultaneously spread in each single-layer trade network, and the dependent relationships between layers in the prestage and the next stage will further aggravate the avalanche size to the layers in the next stage. Therefore, the avalanche size of a given layer is the result of the combined effect of the supply restrictions of the given commodity and the commodities in the prestage.

Figure 8 reflects the important risk sources and their influence on each layer in the GELSN. The top ten risk sources for EV-LIBs include resource-rich countries, such as South Africa and Congo, and technologically advanced countries, including China, South Korea, the USA, Germany, the Netherlands, and Japan. The six highest risk sources have similar impacts on the cathode and EV-LIB layers, although they have greatly different influences on the other layers. In addition, the EV-LIB industry is reliant on mineral resources because of the significant impacts of resource-rich countries (South Africa and Congo), even more so than South Korea and Germany. Therefore, it is necessary to develop technologies for advanced materials and to reduce the dependence on traditional mineral resources. In terms of geographical distribution, Asian countries, including China, South Korea, and Japan, have a critical influence on the robustness of the GELSN. Notably, unlike other countries, supply restrictions in China will have a significant impact on each layer. Therefore, stable Chinese exports are significant with respect to the normal operation of the GELSN.

Note: Countries are sorted by the average avalanche ratio in layers L6, L5, L4, L3, L2 and L1 in order of priority. The layers of the nickel, cobalt, lithium, cathode, anode, and EV-LIB trade networks are represented as L1, L2, L3, L4, L5 and L6, respectively.

Figure 8. Impacts of shocks triggered by the top ten countries for all commodities

6. Discussion

The results of this study provide some clues for the EV-LIB industry and policymakers in different countries involved in the GELSN to stimulate stable development from a systematic perspective. The analytical framework proposed in this study offers an example of how to use a multilayer network model to depict and analyze a global supply network for a certain industry. The implications can be summarized as seven points.

First, Germany, the USA and China play crucial roles in the GELSN. Figure 3 shows the static centrality of countries in the GELSN. Notably, as the most important export countries, South Korea and Japan do not have equivalent positions corresponding to their positions in the EV-LIB single-layer trade network. Most countries with high centrality are located in Europe. Therefore, the core countries in a single-layer network cannot provide an accurate understanding of the intricate GELSN. The core countries identified by the MultiRank algorithm provide a holistic view with which to understand critical risk sources in the GELSN: Policymakers should pay more attention to these core countries.

Second, the degree of activity of influential countries in different stages of the GELSN shows increasing disparity. This result is reflected by the conflict of the increasing trade value of mineral resources and the increasing significance of the single-layer trade networks of intermediate components and finished products in the GELSN. In particular, there is significant growth in the trade value of raw mineral resources, as shown in Figure A2 in Appendix A2. However, under the evaluation based on the MultiRank algorithm, EV-LIBs have an increasing influence, and mineral resources have a declining influence from 2012 to 2020 as shown in Figure 4. This disparity has a negative influence on the stable development of the influential countries in the EV-LIB industry. Therefore, policymakers and practitioners should seize these investment opportunities, positively participate in the raw material market, and improve and standardize the domestic recycling system to improve recycling and the efficient use of resources.

Third, critical risk sources show significant regional and industrial characteristics in single-layer trade networks. As shown in Table 1, supply restrictions imposed by African and South American countries, such as Zimbabwe, South Africa and Chile, will lead to a large proportion of countries collapsing in the single-layer nickel, cobalt and lithium trade networks. In the intermediate component (cathode and anode) and finished product (EV-LIB) trade networks, supply restrictions imposed by some industrialized Asian countries, including Japan, South Korea and China, will lead to large avalanche sizes. These results should alert policymakers to the threat of export reductions in these critical risk countries.

Fourth, improving a country's anti-risk capacity in the six single-layer trade networks will have three different effects on the fragility of a specific trade network. The variation in the avalanche size of shocks caused by a given country with different threshold parameter settings shows three different patterns in Figure 5. Notably, improving the domestic production of commodities involved in the EV-LIB industry is critical to enhance the capacity to resist risks triggered by the reduction in international trade. In this case, the different effects of improving a country's anti-risk on the robustness of the single-layer trade networks offer insights into how to implement an affordable solution to respond to systemic risk. In particular, improving the exploitation and utilization of cobalt resources for countries with a low ratio of domestic production to cobalt imports can considerably enhance the robustness of the cobalt trade network. In addition, a reduction in the ratio of domestic production to lithium/cathode/anode/EV-LIB imports in the corresponding influential countries will lead to an apparent fragility of the robustness of these layers. Changes in these countries should receive close attention from policymakers in other countries to maintain the stability of the trade system.

Fifth, some hidden risks in the multilayer supply network should be taken seriously. Figure 6 shows the highest risk sources in five propagation paths under supply restrictions on a certain commodity. Some hidden risk sources are revealed in consideration of the complex dependent relationships between the upstream and downstream layers. For instance, China has a minor impact on the lithium trade network when restricting supply. However, its influence is expanded through the intricate relationships between lithium and intermediate components. Furthermore, it leads to the largest number of avalanched countries in finished products (EV-LIBs). Similarly, blocked export channels in some resource-rich and undeveloped countries, such as Congo and South Africa, as shown in Figure 8, will have a great impact on finished products (EV-LIBs). These risk sources are always hidden by traditional static methods. Policymakers should pay more attention to these hidden risk sources and make contingency plans for the corresponding risks.

Sixth, it is important to establish the cross-border cooperative mechanism in the EV-LIB industry to promote carbon neutrality. From a global perspective, the robustness of the international EV-LIB trade system is critical to reducing carbon emissions. Policymakers should pay more attention to the critical risk sources found in this study and propose effective strategies to maintain the trade security of the related commodities and the stable development of the EV-LIB industry. From a national perspective, policymakers in a given country should establish strategies based on the country's position in the GELSN and the country's structural characteristics. For critical risk sources in the raw material single-layer networks, it is better to improve the technologies for mining and processing mineral resources and to reduce environmental pollution and carbon emissions. Countries with the advantage in finished products is necessary to provide technical support for the core countries in the raw material layer to reduce carbon emissions in the context of the global development community.

Seventh, the analytical framework used depicts the global supply network with an overall consideration of the intricate trade and supply relationships, and the proposed simulation models provide tools for revealing the shock propagation paths among countries and commodities. This study provides an example of the use of complex network theory to understand the global supply network for a certain industry and expands the application scenarios of the multilayer network model. Meanwhile, due to the simplifications and abstractions of the practical processes and due to the limitations of the simplifying assumptions, the data and the extent to which the processes are understood, there will be uncertainty in the results. Assuming the same anti-risk threshold for different countries due to limited information on the domestic production of commodities in countries will lead to an underestimation of great risk sources. The definition of unweighted and directed connections between upstream and downstream commodities, which ignores the influence from the demand side to the supply side, will underestimate the influence of shocks. In addition, six major commodities are considered in the GELSN, which simplifies the real supply network. The real system of the GELSN is more vulnerable. More analyses of the uncertainty in the results and the sensitivity of the influencing factors in the proposed models are shown in Appendix A6.

7. Conclusion

Previous studies on the international trade of critical mineral resources or EV-LIBs mainly construct classic single-layer trade networks, resulting in an underestimation of the risks of the supply network. This gap provides the motivation for this study to model the GELSN based on a multilayer network model. Critical risk sources are identified from static and dynamic network perspectives, and the main results and implications are summarized.

In consideration of the intricate dependent relationships between commodities in the GELSN, critical stages of the industry are shifting from a focus on upstream mineral resources to a focus on intermediate components and finished products (anodes and EV-LIBs). In addition, the varied importance of related commodities in the supply network redefines the influence of countries, which cannot be simply calculated based on import/export shares. From a holistic view of the multilayer supply network, Germany, the USA and China play a vital role. Despite being the most important export countries in the EV-LIB single-layer trade network, South Korea and Japan do not have equivalent corresponding positions. Under supply restrictions in a single-layer trade network, critical risk sources have prominent regional and industrial characteristics. African and South American countries have a great impact on raw mineral materials, while industrialized Asian countries lead to large avalanches in intermediate and finished products. Considering the shocks in the multilayer supply network, some hidden risk sources are identified, and the limited impact upstream will be amplified to an unexpected scale downstream through the multilayer supply network. The results provide a wider perspective for practitioners in a certain stage of the GELSN to understand systemic risks. The proposed analytical framework offers a tool for policymakers in the countries involved to formulate macroscopic and systemic strategies for the whole industry chain and global trade. In addition, some hidden risk sources are revealed for policymakers to pay more attention to, avoid deficiencies and take necessary action in advance.

Due to the limited statistical data used and some simplifying assumptions in this study, there is some underestimation of systemic risk and uncertainty in the results. To further control this uncertainty, this work could be extended by future work in the following four ways. First, the focus could shift from unweighted links to weighted links if public datasets offer support. Second, research could shift from a focus on unidirectional links to the study of bidirectional links, considering effects from the demand side. Third, for a given country, the variation in the trade volume under shocks can be evaluated in further studies. Fourth, with more reliable statistical data, more commodities can be considered to construct a more realistic GELSN.

Appendix A. Supplementary data

Appendix A1 presents the HS code of the commodities involved in the GELSN and a detailed account of the preprocessing of the data. Appendix A2 briefly introduces the basic structural indicators of the network. Appendix A3 shows the detailed definition of the MultiRank algorithm. The results regarding the structural characteristics of the single-layer trade networks and the relationships between the single-layer trade networks are presented in Appendix A4. Appendix A5 shows the fragility of the single-layer trade networks. Appendix A6 analyzes the uncertainty in the results and the sensitivity of the influencing factors in the proposed models.

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