
Article

Supply Chain Resiliency and Transparency Assessment Using Graph Analytics and Stress Testing

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Abstract

This paper presents a comprehensive methodology for assessing supply chain transparency and resiliency using a data-driven approach. Leveraging global trade data and Harmonized System (HS) codes, the methodology maps each stage of the supply chain to enhance regulatory compliance and mitigate operational risks. Transparency is evaluated using a novel classification system that categorizes branches as fully transparent, highly transparent, moderately transparent, or non-transparent. This enables raw material traceability, Scope 3 greenhouse gas (GHG) emission estimation, and identification of high-emission nodes for targeted reductions. Resiliency is assessed through graph analytics and stress testing, incorporating metrics such as the Giant Connected Component (GCC) and probabilistic simulations to analyze vulnerabilities and develop recovery strategies. A case study on the Cr-13 Steel Drill Pipe supply chain highlights the benefits of incorporating scrap materials for sustainability, alongside challenges related to traceability due to regulatory gaps and non-transparent networks. Monte Carlo simulations identify critical nodes whose disruption significantly affects network connectivity; therefore, resiliency, and transparency. This methodology delivers actionable insights to improve supply chain resiliency, sustainability, and operational efficiency. It is scalable across industries, enabling stakeholders to optimize management strategies, align with global climate initiatives, and build resilient and transparent networks.

Keywords: supply chain resiliency; transparency; graph analytics; stress testing; trade transactions; economic benefits; raw material sourcing; critical minerals; mine tracing

1. Introduction

In today's globalized economy, supply chain transparency, traceability, and resiliency stand out as crucial factors for effective supply chain management. Given the complex nature of supply chains, adding regulatory requirements, consumer expectations, and the universal demand for operational efficiency further emphasizes the necessity for robust frameworks to manage supply chains effectively.

The need for increased transparency and end-to-end traceability in supply chains has become more acute amid multiple driving forces. They include growing environmental concerns that demand accountability, the growing importance of ethical sourcing practices, and mounting pressures from regulatory bodies. Considering that supply chains operate across different jurisdictions and geographical boundaries, the accurate tracing of materials' journey from their raw form to the end product is not just a requirement for

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compliance but also a strategic advantage that companies can leverage in the competitive marketplace. Equally important to transparency is the resilience of supply chains in the face of disruptions, which helps maintain continuity of operations. Recent world events, such as the COVID-19 pandemic and geopolitical tensions, have tested the robustness of supply chains and exposed vulnerabilities in traditional models.

The various supply chains associated with manufactured goods pose significant traceability and, hence, transparency challenges: first, because of the immense heterogeneity of constituents forming part of these manufactured products and those involved throughout the entire manufacturing line. Second, these products are often transported along large, interconnected networks encompassing raw materials and parts supplied by suppliers based in several countries with their own individual regulatory policies and industry codes. The complexity increases due to the number of intermediaries, such as suppliers, manufacturers, and distributors, which makes traceability of each component difficult. Further, variations in technology adoption and data management practices among the stakeholders complicate the consistency and reliability of traceability. A lack of transparency may keep labor practices, environmental compliance, and quality control measures out of sight, posing risks to both the brand and the consumer.

Increased transparency through better tracking technologies and standardized data protocols enables companies to identify inefficiencies, potential risks, and areas of non-conformance, while supporting proactive responses to disruptions and market changes. A resilient supply chain—achieved through flexible sourcing and robust risk management—further ensures operational continuity under diverse scenarios. Therefore, assessing transparency serves a dual purpose: it fulfills regulatory and consumer demands while simultaneously fortifying supply chain resilience, resulting in more robust and reliable manufacturing processes.

1.1. Supply Chain Transparency and Associated Challenges

Supply chain transparency has become a critical aspect of modern industry, driven by multiple forces ranging from regulatory pressures to consumer demands and operational efficiency [1,2]. The global nature of production, where raw materials often cross multiple borders before reaching the final consumer, adds complexity to supply chains [3,4]. Thus, this interconnectedness makes it increasingly difficult for companies to monitor and ensure accountability at every stage of their supply chain networks. As a result, various stakeholders, from governments to consumers, call for greater transparency [5]. The key drivers behind the need for supply chain transparency include regulatory compliance, environmental sustainability, ethical sourcing, risk management, and operational efficiency [6].

Governments worldwide are implementing stricter regulations to require companies to trace their supply chains, primarily to reduce CO₂ emissions and ensure that products meet specific environmental and social standards [7,8]. Policies such as the European Union's Carbon Border Adjustment Mechanism (CBAM) and carbon taxes are examples of precautions designed to reduce the carbon footprint of imported goods for the sake of the environment [9–11]. CBAM, in particular, requires companies importing goods into the EU to account for the embedded carbon emissions in their products, ensuring that products with lower emissions have a competitive advantage [12]. Similarly, carbon taxes are being implemented globally to penalize companies that fail to mitigate their carbon emissions throughout the supply chain [13]. Furthermore, Tost et al. (2020) demonstrate that meaningful carbon pricing at the mine level is essential for meeting Paris Agreement targets, underscoring the need for traceability frameworks that extend to raw material extraction [14]. Therefore, compliance with these policies necessitates robust supply chain traceability and transparency assessment systems that allow companies to track carbon

emissions to reduce them and other environmental impacts from the raw material source to the final product.

The growing emphasis on sustainability and climate action also drives the need for supply chain tracing [15]. Consumers, governments, and non-governmental organizations (NGOs) are increasingly concerned about the environmental impacts of products, especially regarding carbon emissions, deforestation, and water usage [16,17]. Supply chain transparency helps companies identify inefficiencies and high-emission nodes within their supply chain networks, enabling them to take corrective action. Therefore, transparency is crucial for industries with significant environmental footprints, such as mining, manufacturing, and agriculture. By assessing transparency in their supply chain networks, companies can reduce their environmental impact, support global climate goals such as those outlined in the Paris Agreement, and enhance their corporate social responsibility (CSR) initiatives [18,19].

Beyond environmental concerns, the ethical sourcing of materials has become a central issue in supply chain management [20,21]. Consumers and advocacy groups increasingly demand that companies ensure their products are free from exploitative labor practices, such as child labor, forced labor, or unsafe working conditions [21,22]. Therefore, supply chain tracing and transparency provide companies with tools to verify that their suppliers adhere to ethical standards, ensuring that they responsibly source materials. For example, industries like fashion, electronics, and agriculture often face inspections of labor practices in their supply chain networks [23,24]. Recent evidence from European renewable energy technology manufacturers shows that expectations for responsible sourcing are increasingly driven by downstream actors, reinforcing the need for end-to-end supply chain visibility [25].

Supply chain transparency is not only about compliance and consumer demands; it also provides significant operational benefits. Companies can identify inefficiencies by fully understanding their supply chains, such as unnecessary intermediaries, redundant shipping routes, or excessive energy use in production processes. Transparency can help companies to streamline their operations, reduce costs, and improve overall efficiency. For example, identifying a shorter or less resource-intensive supply chain route can significantly reduce transportation costs and carbon emissions [25–27]. Additionally, supply chain transparency enables companies to manage inventory more effectively, reduce waste, and optimize material sourcing, thereby enhancing resiliency, reducing costs, and improving operational performance. However, assessing supply chain transparency and tracing it is challenging due to data unavailability and, most importantly, inconsistencies in reporting standards in a multi-tier supply chain. Sodhi and Tang [28] asserted that visibility beyond the immediate supplier level was challenging due to the opacity of upstream supply chain stages, leading to inefficiencies, risks, and compliance problems. However, shadow flows in scrap and secondary material markets represent a systemic transparency gap that undermines circular economy goals [29].

As the world shifts toward circular economy models, where materials are reused, recycled, or repurposed rather than discarded, supply chain traceability becomes an enabler of this transition [30]. In a circular economy, products and materials are kept in circulation for as long as possible, which reduces demand for virgin raw materials and minimizes waste [31]. Thus, supply chain tracing allows companies to track the lifecycle of materials and products, ensuring that materials can be recovered and reused at the end of their lifecycle. For this reason, transparency and traceability are particularly important for industries that rely heavily on finite resources, such as mining and electronics manufacturing [32]. By supporting circular economy initiatives, companies can reduce their environmental impact and contribute to a more sustainable global economy [33].

The extensive research on LCA incorporates supply chain mapping and tracing using material flow analysis and carbon footprint assessment methods. For example, Hellweg & Milà i Canals (2014) [34] applied LCAs to analyze environmental impacts across the product life cycle and further stated that understanding each supply chain stage was necessary to minimize emissions and improve sustainability. Likewise, in introducing frameworks for material flow analysis and tracking resources through supply chains, Hertwich et al. (2010) [35] address the shortcomings of such approaches in dealing with multi-tiered supply chains at a granular level. Although these approaches provide insights at certain supply chain stages, they usually lack the required scale or granularity to cover the entire supply chain network.

While LCA and material flow approaches illuminate environmental impacts at specific supply chain stages, they fundamentally differ from network-analytic methods in their ability to capture systemic interdependencies, node criticality, and cascading failure dynamics. LCA-based studies typically assume linear material flows and fixed system boundaries, which limits their applicability to multi-tier networks where circular flows, trader intermediaries, and non-traceable branches are endemic. By contrast, graph-analytic frameworks treat the supply chain as a complex adaptive system, enabling identification of structural vulnerabilities that cannot be inferred from material balances alone. This methodological gap motivates the present study.

1.2. Supply Chain Resiliency and Associated Challenges

Along with transparency, the resiliency of supply chains has been brought to the forefront as a priority by recent global events such as the COVID-19 pandemic, natural disasters, and geopolitical tensions [36,37]. These disruptions have exposed vulnerabilities in traditional supply chain structures, emphasizing the need to identify critical bottlenecks and build systems capable of adapting to unforeseen challenges. Resiliency in supply chains is not just about avoiding disruptions but also about ensuring swift recovery and maintaining operational continuity in adverse conditions [38,39]. It involves creating redundancy in critical nodes, diversifying suppliers, and developing robust contingency plans. Identifying critical nodes in a supply chain network necessitates a fully transparent supply chain, indicating that resiliency and transparency are interdependent. Therefore, a resilient and transparent supply chain is better equipped to handle uncertainties and can provide a competitive advantage by minimizing the impact of disruptions on business operations.

Consumers today are more informed and empowered than ever due to easy access to vast information regarding the products they purchase [38]. Increasingly, consumers are demanding to know where their products come from, how they are made, and whether they align with ethical and environmental standards, which has led to a rise in demand for transparency and traceability across various industries [40–42]. Therefore, brands that provide transparent information about their supply chains, such as where raw materials are sourced and how products are manufactured, can build stronger consumer trust. For example, in the food and beverage industry, consumers increasingly expect companies to provide information about the origin of their ingredients, the environmental impact of their production processes, and whether the products are organic or sustainably produced [43]. By providing this level of transparency, companies can cater to the growing demand for ethically and sustainably sourced products, thereby enhancing brand loyalty and consumer trust.

Studies on supply chain resiliency show strategies for mitigating risks of disruptions, such as natural disasters, geopolitical tensions, or pandemics. Ivanov & Dolgui (2021) [44] suggested frameworks for resilient supply chains designed using scenario-based approaches to uncertainty management. Their contribution highlighted redundancy and

diversification, which they consider valuable ways to reduce vulnerability to specific events, without addressing the crucial importance of certain nodes or branches within the whole network. Similarly, Christopher & Peck (2004) [45] underlined a holistic approach toward supply chain risk management while noting the challenges of achieving real-time visibility and dynamic adaptability in highly interconnected networks. The effectiveness of stress testing using Monte Carlo simulations for analyzing resilience in complex networks has been proven by Aydin et al. (2018) [46] in their investigation of transportation networks against geohazard risks.

1.3. The Developed Supply Chain Transparency and Resiliency Tool

In this paper, we respond to the growing need for supply chain tracing and transparency by introducing a methodology to unpack the supply chain network of manufactured goods from the end user to the raw material source and supply chain network resiliency analysis using graph analytics. Unlike other approaches focusing on material balance tracing or conducting lifecycle assessments (LCAs), the developed tool provides a supply chain transparency and resiliency assessment using a data-driven approach. Our methodology leverages the analysis of global trade transaction data and Harmonized System (HS) codes introduced by Saka et al. (2024) [47] and maps each stage of the supply chain network so that compliance with regulations can be checked and associated risks can be reduced. The introduced transparency assessment method traces supply chain branches and classifies the network branches according to their transparency levels. This advances previous efforts, such as Marshall et al.'s (2015) [48], who researched transparency in food supply chains but did not include scalable classification systems of transparency. In addition, the supply chain is fully unpacked and classified, allowing estimation of greenhouse gas (GHG) emissions and their uncertainty at the scope 3 level. Unlike the usual material flow or LCA methods, the proposed approach has a scalable architecture that any industry can use to identify high-emission nodes and implement targeted approaches to emissions reduction.

Additionally, the tool uses the analysis of supply chain transparency as input for resiliency analysis. It assesses the supply chain's resiliency using graph analytics and stress testing adopted by Aydin et al. (2018) [46]. We integrated graph-based metrics like the Giant Connected Component (GCC) with probabilistic simulations to assess recovery strategies and quantify uncertainties in disrupted networks.

To demonstrate the proposed tool's implementation, we considered the supply chain of Cr-13 Steel Drill Pipes, which involves mineral supply chains. The traceability of mineral supply chains faces distinct challenges, primarily because of the complex and frequently unclear characteristics of the networks at play. Minerals, in this case, iron and chromium ores, serving as raw materials, traverse various stages—from extraction to processing and manufacturing—across diverse geographical locations and regulatory frameworks. A significant challenge lies in the absence of standardized reporting and the variability of regulatory requirements across countries, which hinders the tracking of mineral origins and monitoring their movement within the supply chain.

This study addresses the following research question: How can global trade transaction data and graph-analytic methods be combined to quantitatively assess the transparency and resiliency of multi-tier mineral supply chains? To answer this question, the study pursues three specific objectives: (1) to reconstruct an end-to-end supply chain network for a complex manufactured product using HS code-based trade data; (2) to classify supply chain branches according to a novel traceable transparency typology; and (3) to quantify network resiliency through centrality analysis and Monte Carlo stress testing, identifying critical nodes and disruption vulnerabilities.

We conducted stress testing using Monte Carlo simulations of supply chain networks for Cr-13 Steel Drill Pipes to determine the effects of disruptions at critical nodes on the connectivity and transparency of the network. Focusing on supply chain transparency and resiliency, this study introduces a critical tool for improving supply chain resiliency, sustainability, and operational efficiency for supply chain management.

2. Materials and Methods

This study presents a novel methodology to trace the end product, starting from the end-user until reaching out to the raw material source, the mine, using various proprietary global trade transaction data, and assesses the transparency and resiliency of the created supply chain network. During this tracing study, all stages of the product are defined, and the companies that are involved in this supply chain are identified. Figure 1 illustrates the methodology steps.

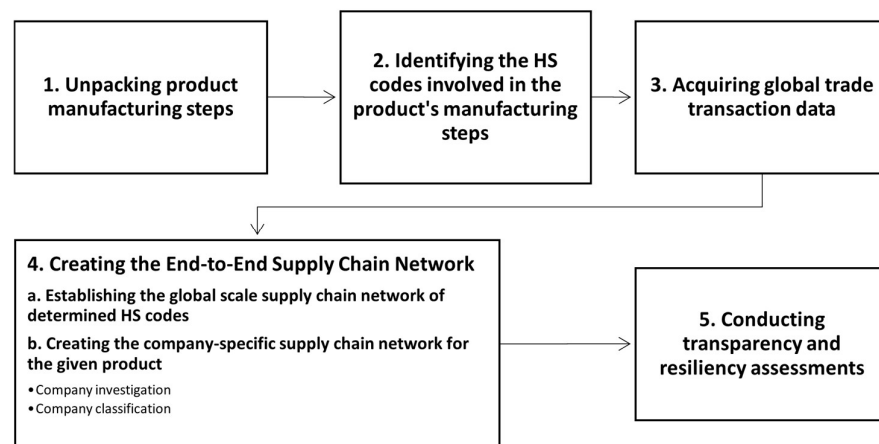


Figure 1. Methodology of end-to-end supply chain company tracing.

As shown in Figure 1, creating an end-to-end supply chain network for a specific end-user starts with unpacking the product's manufacturing steps. The unpacking process includes determining the raw materials and intermediate products, which takes place until the final stage, when the desired end product is obtained. Secondly, given the availability of raw materials, intermediate products, and the final product, the HS codes for each of those materials and products are determined under the global tariff system. Continuing with step 3 in Figure 1, HS codes' proprietary global trade transaction data are acquired to create the company- and product-specific end-to-end supply chain network. Referring to Figure 1, step 4, initially, to analyze the global trade status of the product and the goods taking place in the supply chain, all HS codes are put in sequential order, and all of the transactions are used to create the global scale supply chain network of those raw materials, intermediate products, and the end product. This initial analysis helps determine whether there are trade connections between the company of interest and the raw material sources. After the initial analysis, the end-to-end supply chain network is created by starting at the end user and tracing back to the shipper companies at each stage until reaching the raw material source. During this tracing operation, each company in this supply chain is investigated and classified by its role in the supply chain, such as trader, manufacturer, furnace, forge, etc. As a result of this tracing operation, the final end-to-end supply chain network for the specific company and product is created. The last step of the methodology is to conduct transparency and resiliency assessments by applying graph

analytic methods to determine the critical nodes, transparency, and resiliency of the supply chain network. To assess the transparency of the supply chain network created in step 4 of Figure 1, a new method, traceable transparency, is developed in this study to determine the transparency of each branch in the supply chain network. Finally, by applying this method, the transparency status of each branch is determined. To assess the resiliency of the supply chain network, graph analytic methods are used, namely the giant connected component, degree centrality, betweenness centrality, closeness centrality, and eigenvector centrality. As the last step of the resiliency assessment, stress testing using Monte Carlo simulations is conducted to identify vulnerabilities, evaluate alternative recovery strategies, and estimate the system recovery performance for a range of disruption scenarios.

3. Implementation of the Methodology to a Cr-13 Steel Drill Pipe Supply Chain

In this study, we considered a company's Chromium-13 Steel Drill Pipe supply chain network and unpacked it. The drill pipes are traced back to the mines; an end-to-end supply chain network is created. Then, graph analytics methods are used to determine the critical nodes, resiliency, and transparency of the network.

By following the methodology steps in Figure 1, firstly, the Cr-13 Steel Drill Pipe production steps are investigated and identified. Secondly, HS codes for each good input and output at each step are determined, and data on all HS codes of interest are obtained from various proprietary global trade transaction data. By using all trade transaction connections for this particular end product, the Global Supply Chain Network for this end product was created to analyze the global condition of the end product's supply chain. After analyzing the global picture, starting from the end-user, shipper companies are traced until reaching out to the raw material sources, mines. During this specific tracing, each company's public website and company profile are searched to obtain more information about the company's business, using Generative AI for the company's role classification. Finally, by using data obtained from this HS code and shipper company tracing, the complete end-to-end Supply Chain Network for the Cr-13 Steel Drill Pipe was created.

3.1. Unpacking the Cr-13 Steel Drill Pipe Production Steps

The process of producing a Cr-13 Steel Drill Pipe begins with raw materials from mines. The major ingredient of CR-13 Steel Drill Pipe is iron ore. The other one is chromium ore, which provides the desired characteristic properties of the final product. The iron ore is produced in mines and undergoes a beneficiation process to increase its iron content, called iron concentrate. After this beneficiation process, the iron concentrate is sent to the ironmaking facility, which can be either a Blast Furnace (BF) or a Direct Reduced Iron (DRI) furnace. In this step, the iron is produced and sent to the steelmaking facility, either a Basic Oxygen Furnace (BOF) or an Electric Arc Furnace (EAF). Chromium is the primary alloying element that provides the corrosion resistance and strength characteristic of Cr-13 Steel. Minor quantities of other alloying elements, including manganese, silicon, and carbon, are also adjusted during steelmaking to achieve the desired mechanical properties. As these minor alloying elements are added in small fractions and are not the primary driver of the supply chain structure, they are not separately traced in this study; the focus remains on the dominant iron and chromium inputs. Then, the initial steel is forged and cast to obtain the Cr-13 Steel Drill Pipe.

3.2. Identifying the HS Codes Involved in the Product's Manufacturing Steps

Harmonized System (HS) codes are used to classify the goods traded globally [49]. Every good traded has an HS code according to its specifications. By looking at an HS

code, the specification of the goods traded can be easily known and classified. To identify a good starting point for the end-user until reaching out to the raw material mines, the production steps of the end-product are determined. Secondly, by investigating each production step, input materials and output products are determined. Finally, HS code chapters of the input materials and output products traded in each step are determined as follows [50]:

- HS Code 2601: Iron ores and concentrates, including roasted iron pyrites;
- HS Code 7201: Pig iron and spiegeleisen in pigs, blocks, or other primary forms;
- HS Code 7304: Tubes, pipes, and hollow profiles, seamless, of iron or steel.

Increasing the number of digits of the HS codes will make the goods of interest more specific. A detailed explanation of the abovementioned HS codes is presented in the table below.

Table 1 presents the hierarchical structure of the three HS code chapters relevant to this study. Chapter 26 covers iron ores and concentrates in their raw and processed forms, distinguishing between agglomerated and non-agglomerated types. Chapter 72 classifies pig iron according to its phosphorus content and alloy composition, reflecting differences in material purity and grade. Chapter 73 focuses specifically on subheading 7304.24, which corresponds to drill pipe used in oil and gas drilling operations—the end-product of the supply chain traced in this study. Together, these codes enable systematic tracking of materials from raw ore extraction through to the final manufactured product.

Table 1. Full description of Harmonized System (HS) codes and their subheadings relevant to the iron-ore-to-steel-pipe supply chain [50].

HS Code	Description
Chapter 26—Ores, Slag, and Ash	
2601	Iron ores and concentrates, including roasted iron pyrites
2601.11	Non-agglomerated iron ores and concentrates
2601.12	Agglomerated iron ores and concentrates
2601.20	Roasted iron pyrites
Chapter 72—Iron and Steel	
7201	Pig iron and spiegeleisen in pigs, blocks, or other primary forms
7201.10	Non-alloy pig iron containing by weight 0.5% or less of phosphorus
7201.20	Non-alloy pig iron containing by weight more than 0.5% of phosphorus
7201.50	Alloy pig iron; spiegeleisen
Chapter 73—Articles of Iron or Steel	
7304	Tubes, pipes, and hollow profiles, seamless, of iron or steel
7304.24	Drill pipe of a kind used in drilling for oil or gas, of stainless steel

3.3. Acquiring Global Trade Transaction Data

The Drill Pipe Buying Company has more than 200 subsidiary companies worldwide. In order to conduct this tracing study, the Drill Pipe Buying Company provided a list of 11 subsidiaries representing its primary drill-pipe procurement operations—specifically those subsidiaries responsible for upstream sourcing of steel drill pipe across its main geographic markets. The remaining subsidiaries were excluded from the scope because they

operate in downstream distribution, logistics, or adjacent product lines (e.g., services, non-drilling equipment) that are not part of the Cr-13 Steel Drill Pipe supply chain. This focused selection ensures that the reconstructed network captures all relevant upstream trade activity for the product of interest. Various proprietary global trade transaction data were obtained according to the abovementioned HS codes to investigate the complete global end-to-end Cr-13 drill pipe network. The proprietary trade datasets used in this study contain shipment-level records including shipper and consignee names, HS codes, commodity descriptions, weights, and transaction dates. These datasets aggregate trade declarations reported to customs authorities across multiple jurisdictions; however, coverage varies by country, as not all nations mandate public disclosure of bilateral trade data. This creates a structural data bias whereby supply chain branches originating in or transiting through low-reporting jurisdictions are more likely to appear as non-transparent. This limitation is explicitly acknowledged in the transparency classification and should be considered when interpreting resiliency results. In addition, during the specific tracing starting from the Drill Pipe Buying Company until reaching out to the iron and chromium mines, the companies involved in these transactions are investigated by searching their publicly available websites and company profiles to classify them in the final unpacked end-to-end supply chain network. In order to assign classes to each company in the supply chain network, Generative AI-assisted firm classification was used as a first-pass screening tool to assign company roles based on publicly available website content and trade profiles. All AI-generated classifications were manually verified by the research team against company registration records and product catalogs. This hybrid approach reduces the risk of misclassification while maintaining scalability.

3.4. Creating the End-to-End Supply Chain Network

In the beginning, the various proprietary global trade transaction data with the HS codes mentioned in Section 3.2 were obtained. The data for HS codes 2601, 7201, and 7304 were merged, and each dataset was given a color code according to its HS code. As a result of this merging operation, the complete supply chain trade transaction data for the Cr-13 Steel Drill Pipes was ready. Finally, this dataset was used to create the global supply chain network of the Cr-13 Steel Drill Pipes.

To obtain the end-user-specific supply chain network, the tracing starts from the end-user and continues backward by finding the shipper companies in each step, as illustrated in Figure 1. During this shipper company tracing, HS Codes are checked for each step to find the transactions that contain the HS codes 2601, 7201, and 7304. At each step, revealed shipper companies are checked against HS codes and the goods traded. After reaching out to the mines by tracing operations, the complete end-to-end Cr-13 Steel Drill Pipes supply chain network for the buyer company is created.

Stakeholder classification was performed using deterministic criteria applied to each company's publicly available trade records and business profile. A company is classified as a Subsidiary if it is owned by or operates under the corporate umbrella of the Drill Pipe Buying Company. A Trader is a firm that appears as both shipper and consignee across multiple HS-code categories without evidence of physical transformation or production capacity. A Manufacturer is a firm whose receiving shipments include raw or intermediate materials and whose outbound shipments include finished or semi-finished drill pipe products. A Mining Company is a firm whose outbound shipments are dominated by HS 2601 (iron ore and concentrates) and whose operations are verified against public mining registries. Electric Arc Furnace and Blast Furnace operators are classified based on outbound steel shipments (HS 7201–7206) combined with company profile verification. Forge operators are identified by the combination of receiving steel inputs and outbound shipping of shaped steel articles (HS 7304). In cases where trade records alone were insufficient,

company websites and industry registries were used to confirm role assignments. These criteria were applied consistently across all 127 nodes in the reconstructed network.

The companies that took part in this supply chain are also classified as follows:

- Subsidiary;
- Trader;
- Manufacturer;
- Forge;
- Mining Company;
- Electric Arc Furnace;
- Blast Furnace;
- Iron Mine;
- Chromium Mine.

Since the data is not fully transparent, it is challenging to trace all branches of the supply chain to their end. The end nodes of those branches that are not completely transparent are also classified as follows:

- Trader Loop;
- Scrap Supply;
- Chromium Supply.

An asymmetry in the terminal node categorization is noted: the network includes a ‘Chromium Supply’ category but no corresponding ‘Iron Supply’ category. This reflects the observed structure of the trade data rather than a modeling choice. In this case study, chromium inputs were traceable to a single node (Trader-11) whose supplier could not be identified through trade records or generative AI-assisted company profiling, resulting in the need for a dedicated ‘Chromium Supply’ terminal node. By contrast, all iron inputs were either traceable to specific mining companies or iron mines, or to scrap supply sources—none resulted in an unresolved supplier of the type that required an ‘Iron Supply’ category. Should future applications of this methodology encounter equivalent ambiguity on the iron side, an ‘Iron Supply’ category would be introduced analogously.

3.5. Conducting Transparency and Resiliency Assessments

In this study, transparency assessment is conducted using a novel graph analysis method developed to classify the branches of a supply chain network in terms of transparency, called the traceable transparency method. This method classifies branches into Fully Transparent, Highly Transparent, Moderately Transparent, and Non-Transparent. The classification thresholds are operationalized as follows: a branch is assigned to the highest applicable category based on its terminal node type. If a branch terminates at both an iron mine and a chromium mine, it is classified as Fully Transparent. If it terminates at only one mine type, it is Highly Transparent. Branches terminating at trader loops, scrap supplies, or chromium supply nodes are classified as Moderately Transparent. Branches that terminate at a company node from which no further tracing is possible—due to non-disclosure or reporting gaps—are classified as Non-Transparent. These rules are applied deterministically; there is no partial or probabilistic assignment.

To assess the resiliency of the supply chain network, first, the critical nodes of the supply chain network are identified using the giant connected component, degree centrality, betweenness centrality, closeness centrality, and eigenvector centrality. The parameters used to calculate the abovementioned centrality metrics are listed in Table 2.

Table 2. Explanations of the variables used in the equations of the graph analysis methods.

Variable	Explanation
GCC	Largest connected component
$C_1, C_2, \dots, C_k$	Connected components of the graph
$C_D(v)$	Degree centrality of node v
$\deg(v)$	Degree of node v , defined as the number of edges incident to v (i.e., the number of direct trade connections); does not refer to angular measure
N	Total number of nodes in the graph
$C_B(v)$	Betweenness centrality of node v
n_{st}	Total number of shortest paths between nodes s and t
$\sigma_{st}(v)$	Number of those shortest paths passing through node v
$C_C(v)$	Closeness centrality of node v
$d(v, u)$	Shortest distance between node v and node u
u	Any other node in the graph
x_i	Eigenvector centrality of node i
A_{ij}	Adjacency matrix entry, indicating a connection between node i and node j
x_j	Eigenvector centrality of node j
λ	Eigenvalue

The graph analysis methods considered in this study to determine the most critical node in the supply chain network are listed in Table 3.

Table 3. Graph analysis methods.

Graph Analysis Metric	Equation	Measure
Giant Connected Component	$GCC = \max(C_1, C_2, \dots, C_k)$	Largest Node Group
Degree Centrality	$C_D(v) = \frac{\deg(v)}{N-1}$	Direct Connections
Betweenness Centrality	$C_B(v) = \sum_{s \neq v \neq t} \frac{n_{st}(v)}{n_{st}}$	Path Bridging
Closeness Centrality	$C_C(v) = \frac{N-1}{\sum_t d(v, u)}$	Reach Efficiency
Eigenvector Centrality	$x_i = \frac{1}{\lambda} \sum_j A_{ij} x_j$	Influential Connections

As shown in Tables 2 and 3, the giant connected component provides the largest connected subgraph in a particular network and represents the main network body where most nodes are connected. Degree centrality measures the number of connections each node has in the network and reflects how important a node is, depending on its neighbors. Betweenness centrality is used to quantify how many times a node acts as a bridge along the shortest path between the other two nodes in the path. The closeness centrality measures the distance of each node to all other nodes in the network. Lastly, eigenvector centrality measures each node's influence based on its connections to other highly connected nodes, and it considers both the quantity of the connections of each node and the quality of them.

Then, the critical nodes of the network are disrupted in a stress-testing process using Monte Carlo simulations. As introduced by Aydin et al. (2018) [46], stress testing using Monte Carlo simulations is one of the efficient ways to assess the strength of complex networks against uncertainty. Resiliency is defined as the ability of a network to resist perturbations, recover functional capability, and adapt to negative events; it is crucial for maintaining the functionality of interconnected systems such as supply chain networks. The Monte Carlo analysis considers uncertainties in a network, reflecting variability in recovery times and node failures across different potential scenarios. This methodology

allows the identification of vulnerabilities, the evaluation of alternative recovery strategies, and the estimation of system recovery performance for a range of disruption scenarios. Functioning as a probabilistic approach, it affords decision-makers crucial insights into the robustness and adaptability of the network, thereby enabling informed decisions aimed at improving overall resiliency.

In this study, nodes in the network are removed to simulate disruption with a 10% probability, a moderate stress-test value for networks. The 10% node-removal probability was selected as a moderate disruption intensity, consistent with the stress-testing approach adopted by Aydin et al. (2018) [46] for complex network resilience assessment under uncertainty. This value represents a balance between capturing realistic disruption scenarios and preserving sufficient network structure for meaningful analysis of cascading effects. Firstly, to determine the point at which the results stabilize, a number of Monte Carlo simulations are run to calculate average resilience scores, starting with 1000 simulations and increasing to 512,000 simulations. Then, the first point at which the results stabilize is chosen as the optimal number of simulations, which provides computational efficiency. This optimal number of simulations is used to assess the resiliency of the supply chain network under random disruptions and failures.

4. Results and Discussion

4.1. End-to-End Supply Chain Network

By obtaining and using the determined HS code data, the global supply chain network was created to see the condition of our end-product on a global scale, as illustrated in Figure 2.

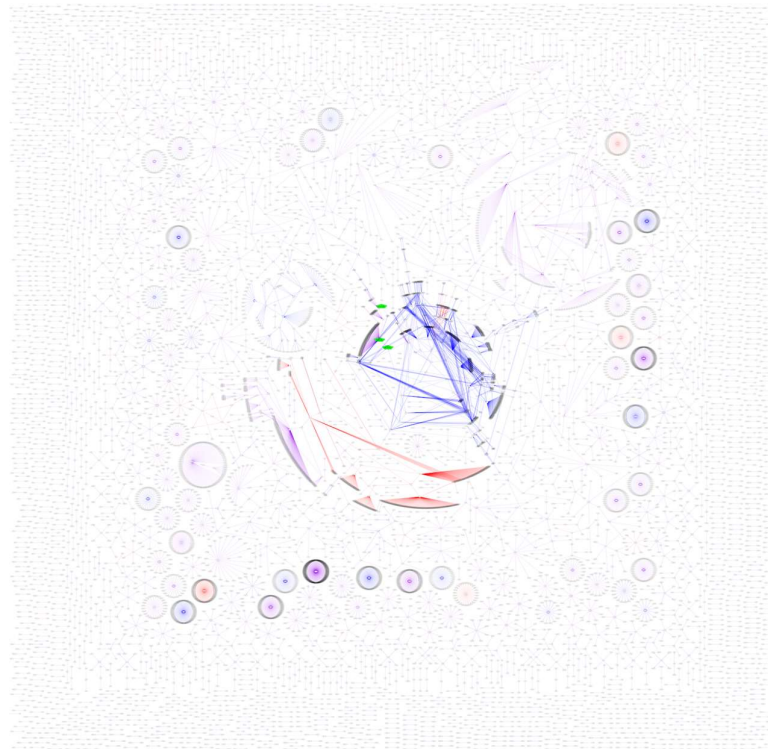


Figure 2. Trades of the Drill Pipe Buying Company on a global scale.

As shown in Figure 2, the Drill Pipe Buying Company is marked with green pentagons. The red arrows indicate the flow of iron ore and concentrate transactions (HS Code: 2601), the dark blue arrows represent the flow of pig iron transactions (HS Code: 7201),

and the purple arrows show the flow of steel drill pipe transactions. By following the sequential flow from purple to dark blue and from dark blue to red, the Cr-13 Steel Drill Pipes can be traced backward. However, since this supply chain network model spans the globe, it is extremely challenging to trace goods from end users to the mines that supply raw materials. As shown in Figure 2, the network contains many circular shapes in each color. These circular shapes indicate that those nodes are non-traceable because they do not have any other connections to any other sub-network. As mentioned, the company of interest is marked with a green pentagon shape. Therefore, in order to trace the transactions of this company, the following sequential color codes must be used: purple, dark blue, and red. By following this sequential flow, the good can be traced back to the raw material mine, and the interpretation is extremely challenging in Figure 2. However, Figure 2 helps to understand the global position of the company of interest for the Cr-13 Steel Drill Pipes. Although the graph includes all the colors and valuable connections, the dataset used contains many unknown companies, which makes tracing challenging. The graph in Figure 2 shows that there are very few fully connected nodes following the abovementioned sequential color code present in the graph. This limitation indicates that the supply chain is highly non-transparent, making it challenging to trace goods from the end user to the raw material source. Furthermore, the low number of sequential color code flows shows that the number of legal trade reports is very small.

After reviewing the company's global position, the tracing operation began by analyzing the company's trade transactions. As a result, a fully unpacked supply chain network for the particular product of interest was created and illustrated in Figure 3.

Figure 3 presents a fully unpacked supply chain network for the Cr-13 Steel Drill Pipe of the company. The red arrows are for the flow of iron ore transactions, the green arrows are for steel transactions, the dark blue arrows are for steel articles, and the orange arrows show the flow of chromium transactions. The elliptic nodes represent the companies involved in this supply chain, and the colors of those nodes indicate their class. The pink color is for the subsidiary companies of the Drill Pipe Buying Company; the light and dark green colors are for companies with Electric Arc and Blast Furnaces; the cyan color is for trader companies; the brown color is for forges; and the white color is for the mining companies. The gray rectangular nodes represent the trader loops, the blue rectangular nodes show the scrap supply, and the orange rectangular nodes indicate the chromium supply. Finally, the cylinder nodes show the mines, which are the final nodes for our tracing study. The cylinder node with red color indicates the iron mine, and the orange cylinder node shows the chrome mine. The company names are not available in Figure 3 due to the non-disclosure agreement with the cooperating company, the Drill Pipe Buying Company. However, the names of the companies involved in this supply chain are assigned to their respective classes, such as Subsidiary-1, Trader-1, etc.

This supply chain network model provides the following insights to the stakeholders:

- Supply Chain steps can be traced back, and trader companies can be disintermediated to reach the manufacturers to purchase the goods at more economical prices.
- GHG emissions can be reduced by disintermediating the trader companies. By disintermediating those companies, the transportation distance of the goods can be lowered, resulting in lower GHG emissions.
- By learning the material and good provider companies in the supply chain, stakeholders can find lower GHG-emitting alternatives to decrease their carbon emissions.
- Due to the carbon emission regulations, companies are required to pay taxes for their CO₂ emissions, and those regulations are getting harsher day by day. By lowering CO₂ emissions, companies can profit from decreasing their CO₂ taxes.
- Lowering the GHG emissions will support reaching the Paris Agreement's 1.5 °C temperature increase limitation target [51,52].

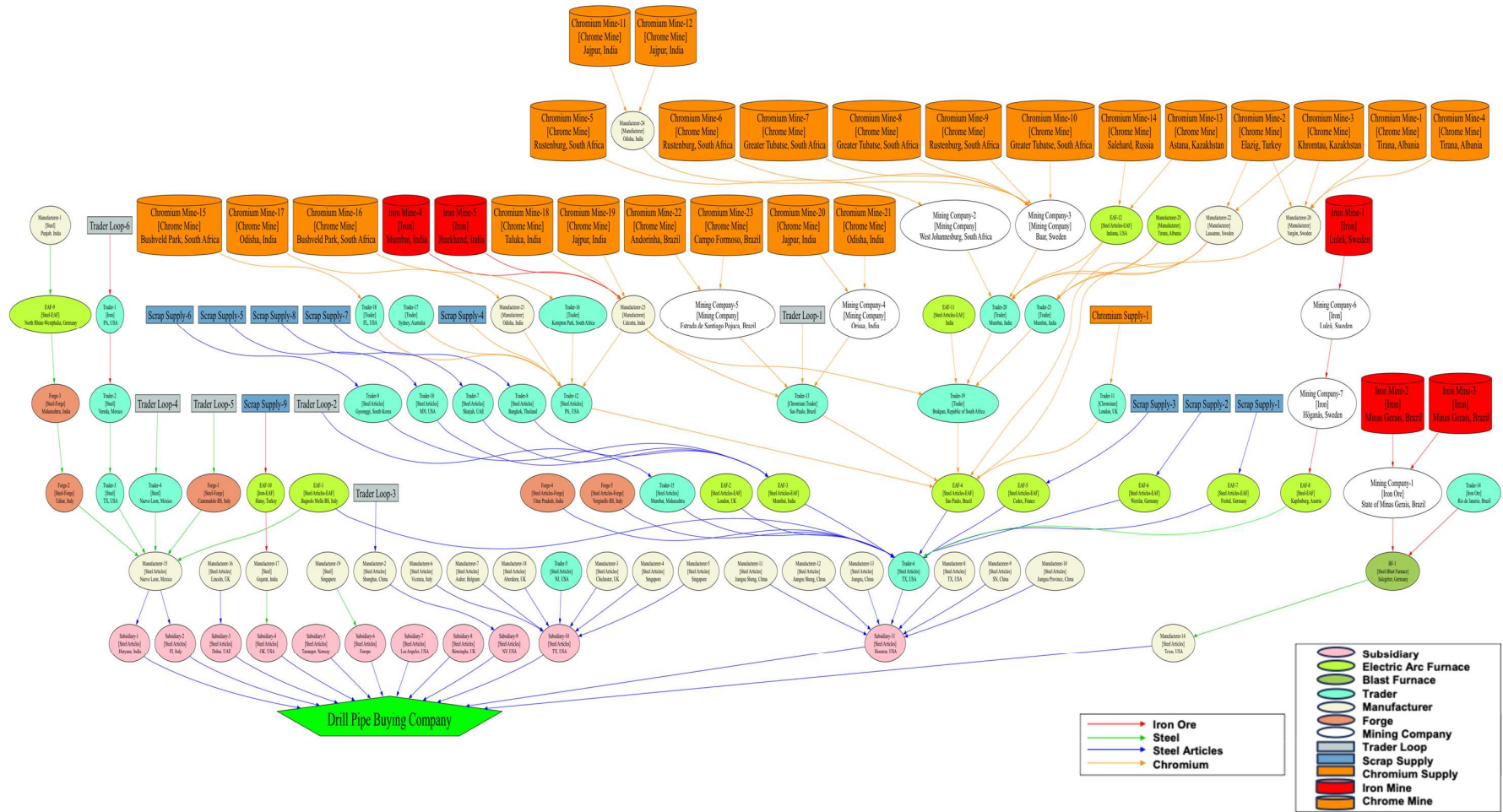


Figure 3. Complete end-to-end Cr-13 Steel Drill-Pipe supply chain network of the buyer company.

Even though Figure 3 provides a fully unpacked supply chain for the drill pipe-buying company, the raw material sources are not identified. The reasons for this gap are limitations in the dataset, deficient reporting of trades to the authorities, and trades conducted within the same company group.

4.2. Transparency and Resiliency Assessments

4.2.1. Transparency Assessment

The traceable transparency method, proposed in the methodology section, was used to classify the branches of the supply chain network according to their transparency status. Due to the large number of nodes and branches in Figure 3, interpreting each of the branches individually is not possible. However, all types of branch transparencies and example routes of them are illustrated in Table 4.

Table 4. Traceable transparency status and example routes.

Traceable Transparency Status	Supply Chain Route
Fully Transparent	[Iron Mine-4 and Iron Mine-5, Chromium Mine-18 and Chromium Mine-19], Manufacturer-23, Trader-12, EAF-4, Trader-6, Subsidiary-11, Drill Pipe Buying Company
Highly Transparent	[Iron Mine-2 and Iron-Mine-3], Mining Company-1, BF-1, Manufacturer-14, Drill Pipe Buying Company
Moderately Transparent	Scrap Supply-9, EAF-10, Manufacturer-17, Subsidiary-4, Drill Pipe Buying Company
Non-Transparent	Manufacturer-1, EAF-9, Forge-3, Forge-2, Manufacturer-15, Subsidiary-1, Drill Pipe Buying Company

The other branches can be assessed using the traceable transparency method and classified accordingly. A fully transparent branch, as shown in Table 4, was identified, as it starts at the end user and reaches both iron and chromium mines. This branch provides a complete end-to-end Cr-13 Steel Drill Pipe supply chain route. By using this branch, GHG emissions can be quantified to identify low-emission alternatives across the full supply chain.

The highly transparent branch was determined since that branch starts from the end-user and reaches one of the raw material sources, an iron mine in this case. Similar to the fully transparent branch case, this route can be used to calculate GHG emissions and identify low-emission alternatives to reduce overall emissions, specifically for the iron ore part in this case.

For the moderately transparent supply chain route, the branch starts at the end user and ends at a scrap supply node. Reaching the scrap supply can be considered a good result because steel production using scrap is one of the key processes in modern steelmaking with EAF. Steelmaking using scrap as raw material contributes to decreasing GHG emissions by considerable amounts, which makes it an environmentally friendly production method. However, the challenge in tracing the scrap supply is that after a point in the supply chain, it is not traceable. The primary reason for this traceability issue is that scrap can be collected or traded locally by waste collectors or other similar parties, and those transactions are not traceable. To conclude, scrap is considered a raw material, but its source cannot be traced; that is why the scrap supply node is classified as moderately transparent.

On the other hand, the branches reach trader loops, and the chromium supply, as the final node, is also classified as moderately transparent. Trader loops stand for the iteratively continuing trader network. Because of these extensive supply chains, tracing goods back to their raw material sources is challenging. To overcome this issue, high

computational power is required. As shown in Figure 3, only one chromium supply node is connected to the Trader-11 node in this supply chain network. The reason for this is that, based on the HS code, shipper tracing and validation, and an extensive generative AI search of the company profile for Trader-11, it was revealed that the company is buying chromium, but the shipper was unknown. Thus, the chromium supply was considered as a raw material, but the source could not be determined, resulting in a traceable transparency classification of moderately transparent.

Lastly, the branch was classified as a non-transparent branch because it starts at the end user and reaches a company node, and it is not traceable after that node. The reason for this non-traceability issue can be that the countries of the shipper companies or the country of the buyer company, Manufacturer-1, are not reporting their trade transaction data. According to the laws and regulations of each country, they may not be required to report their trade data publicly. Moreover, the company may not be reporting its trade transaction data. These non-traceable nodes make their supply chain branches non-traceable and classify them as non-transparent branches.

By using the traceable transparency method, the complete end-to-end supply chain network in Figure 3 was analyzed, and all branches in this supply chain network were classified; the statistics are tabulated below.

As presented in Table 5, the supply chain network in Figure 3 consists of 127 nodes, and the 94 identified supply chain routes are distributed across four transparency classes. Fully Transparent routes account for 13% of all routes, representing cases where both iron ore and chromium mining origins are traceable through a shared convergence node. Highly Transparent routes constitute the largest share alongside Non-Transparent routes, each at 34%, reflecting that a significant portion of routes can be traced to a single primary mining source, while an equally significant portion originates from intermediate actors whose upstream suppliers remain unknown. Moderately Transparent routes account for 19% of all routes, covering cases where the terminal source node is identifiable—whether a scrap yard, trader loop, or unverified chromium supplier—but cannot be linked to a confirmed primary geological origin. In total, 47% of routes (Fully and Highly Transparent combined) are traceable to at least one primary mining source, while the remaining 53% exhibit partial or no upstream visibility, underscoring the structural traceability gaps that persist within the supply chain feeding into the Drill Pipe Buying Company.

Table 5. Traceable Transparency Method application to the end-to-end supply chain network in Figure 3.

Transparency Class	Number of Branches	Percentage
Fully Transparent	12	13%
Highly Transparent	32	34%
Moderately Transparent	18	19%
Non-Transparent	32	34%

Applying the traceable transparency method across all branches of the network reveals that the majority fall into the highly transparent and non-transparent categories, while fully and moderately transparent branches constitute a smaller subset reaching verified raw material sources. This distribution reflects both the structural opacity of multi-tier mineral trade networks and the country-level reporting gaps documented in Section 3.3, which systematically limit end-to-end traceability in jurisdictions with limited public disclosure of trade data.

4.2.2. Resiliency Assessment

To analyze the complete end-to-end Cr-13 Steel Drill Pipe supply chain network of the Drill Pipe Buying company in Figure 3, the giant connected component was found by applying the giant connected component analysis in Table 3. As a result of this analysis, the giant connected component present in the complete end-to-end Cr-13 Steel Drill Pipe supply chain network was identified as the graph shown in Figure 3.

In Figure 3, the largest subgraph in which any two nodes are connected by a path was found. In other words, there is connectivity between them within the giant connected component. According to the graph analysis, this is the core of the graph, showing the most interconnected part. As expected, the giant connected component contains all types of nodes specified in the legend, especially raw material sources, iron and chromium mines, scrap supplies, and furnaces. Having mines, scrap supplies, and furnaces, it is possible to produce the end product for the end user, indicating the supply chain network's high resiliency. Since the giant connected component is the entire graph, the graph is fully connected, which means every node is reachable from any other node in the graph. In other words, there are no isolated or disconnected parts in the network.

The centrality metrics in Table 3 were applied to the complete end-to-end Cr-13 Stainless Steel Drill Pipe supply chain network of Drill Pipe Buying Company in Figure 3 to determine the most critical node with different measures, and the results of that analysis are illustrated in Table 6.

Table 6. Results of centrality metrics.

Centrality Metric	Centrality Value	The Most Critical Node
Degree Centrality	0.10	Drill Pipe Buying Company
Betweenness Centrality	0.68	Trader-6
Closeness Centrality	0.30	Trader-6
Eigenvector Centrality	0.42	Trader-6

According to Table 6, the result of the degree centrality method shows that the most critical node is the Drill Pipe Buying Company, with a centrality value of 0.10. This result indicates that the Drill Pipe Buying Company is directly connected to a significant number of other nodes, and it has a high number of direct connections in the network. Even though its degree centrality is not extremely high, it is the highest value among all other nodes.

Using the betweenness centrality method, the most critical node is determined as Trader-6, which means it lies on a high number of shortest paths between the other node pairs. This node serves as a crucial bridge for facilitating the flow of goods in the supply chain network. The betweenness centrality value of 0.68 indicates a significant role in maintaining network connectivity.

As a result of the closeness centrality method, the Trader-6 is identified as the most critical node with a closeness centrality value of 0.30. This means that the Trader-6 can reach other nodes in the network more quickly than the other nodes. Compared to the other nodes in the network, this node has the lowest average shortest-path length to all other nodes in the network, which shows its efficiency in obtaining and shipping goods.

According to the eigenvector centrality method, Trader-6 has the highest eigenvector centrality value with 0.42, suggesting that it is influential not just because of its own connections but also because it is connected to other well-connected nodes in the network. Trader-6 can be said to occupy a central position in the network, enabling it to quickly access resources and enhance operational efficiency. Therefore, Trader-6 plays a crucial role in improving collaboration, contributing to the overall stability and resilience of the supply chain network.

In conclusion, the analysis of centrality metrics highlights the varying roles and significance of nodes within the supply chain network. While the Drill Pipe Buying Company is identified as the most critical node by degree centrality due to its extensive direct connections, Trader-6 emerges as the pivotal node across multiple centrality methods. Its high betweenness centrality underscores its role as a critical bridge, facilitating connectivity, while its top-ranking closeness and eigenvector centrality values emphasize its efficiency in reaching other nodes and its influence due to connections with well-connected entities. These findings demonstrate that Trader-6 is integral to the network's resilience and efficiency, playing a key role in resource accessibility and operational collaboration.

From a practical standpoint, these centrality findings translate into concrete decision-making guidance for mining supply chain managers. Degree centrality identifies direct exposure—nodes whose disruption immediately affects the largest number of trading relationships, making them priority candidates for dual-sourcing arrangements. Betweenness centrality flags structural bottlenecks—nodes through which the majority of shortest trade paths pass, where redundancy investments yield the highest network-wide resilience gains. Closeness centrality highlights response-time vulnerabilities—nodes whose removal increases the average distance between remaining suppliers and buyers, directly affecting recovery speed after disruption. Eigenvector centrality surfaces influence-weighted dependencies—nodes whose importance derives not only from their own connections but also from their embeddedness among other well-connected actors, typically indicating strategic negotiation leverage points. Collectively, these metrics provide a tiered decision framework: managers can prioritize contingency planning around high-betweenness nodes, diversification around high-degree nodes, and relationship management around high-eigenvector nodes.

Stress Testing using Manto Carlo is conducted by removing nodes from the network with a 10% probability, a moderate stress testing value for networks. To determine the point at which the average resilience score results stabilize, a number of Monte Carlo simulations were run, starting with 1000 simulations and increasing to 512,000 simulations. The change in average resilience scores over the number of simulations is plotted in Figure 4.

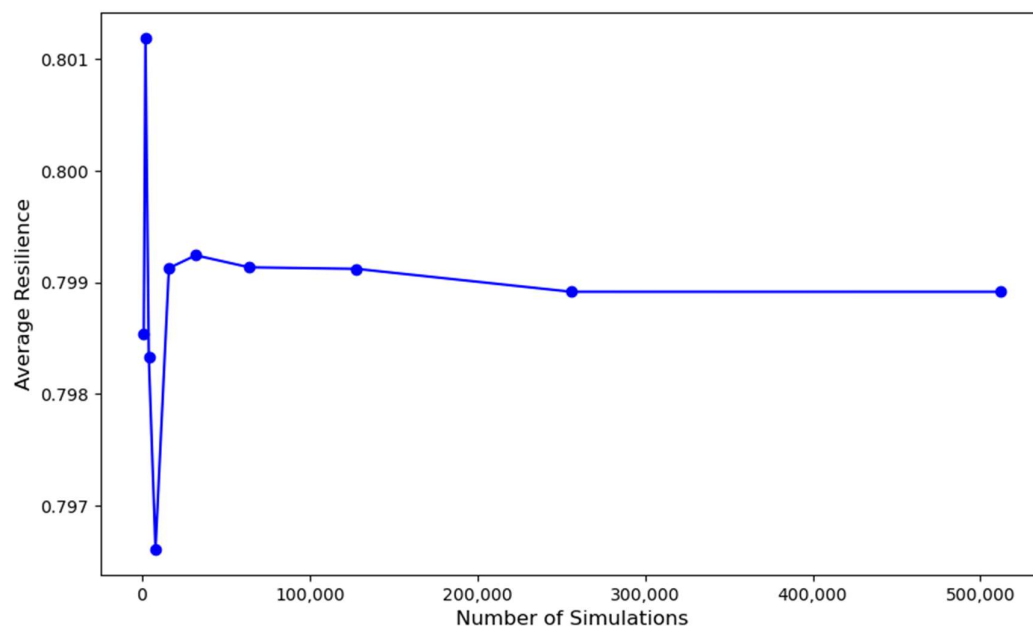


Figure 4. The change in average resilience scores over the number of simulations.

As shown in Figure 4, the lower number of simulations has high fluctuations in the average resilience score. However, with the increasing number of simulations, the graph is stabilized after 256,000 simulations with an average resilience score of 0.80. Therefore, 256,000 simulations are accepted as the optimal simulation number for stress testing using Monte Carlo simulations due to computational efficiency. Having determined the optimal number of simulations, stress testing using Monte Carlo simulations is conducted with 256,000 simulations, and a resilience score over the simulation number is presented in Figure 5.

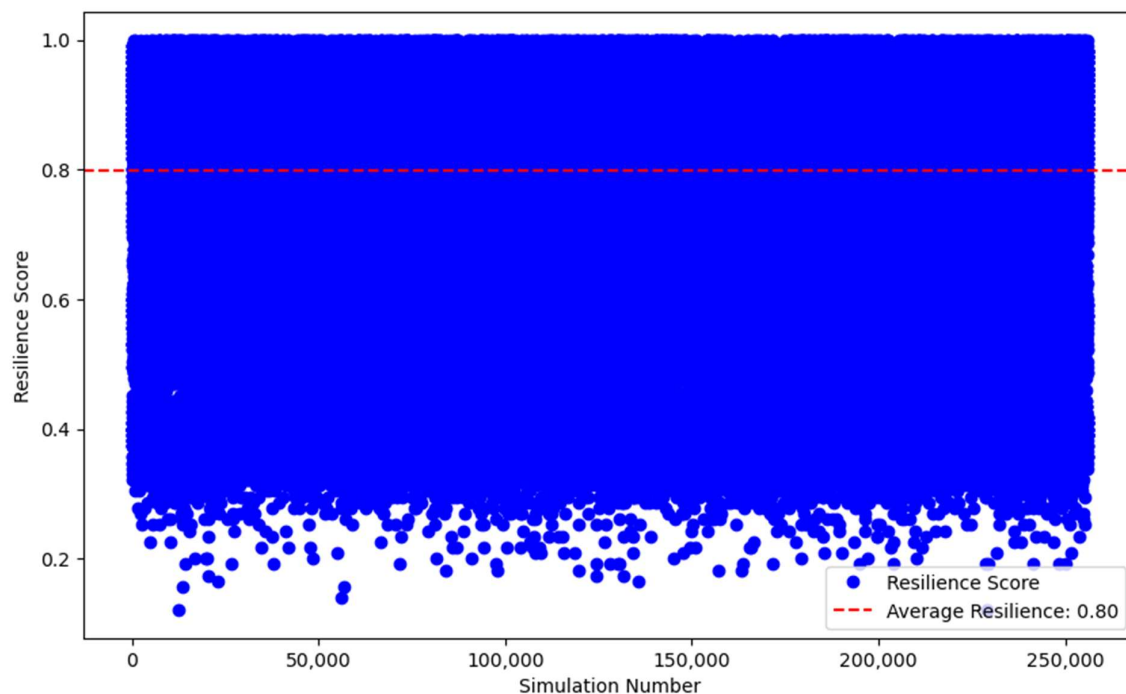


Figure 5. Resilience score across 256,000 Monte Carlo simulations. The distribution spans from a minimum of 0 to a maximum of 0.85, with an average of 0.80 (indicated by the dashed horizontal line). The density of points around the mean reflects the central tendency of network behavior under 10% random node disruption, while the dispersion at the extremes characterizes worst-case and best-case scenarios.

Figure 5 illustrates the random disruption scenarios randomly applied to the supply chain network in Figure 3 and the change in the resilience score. According to Figure 5, the minimum value of the resilience score is 0.15; the maximum is 1; and the average resilience score was calculated as 0.80 over 256,000 simulations. A resilience score of 0.80 indicates that, under the simulated disruption conditions, the network retains, on average, 80% of its pre-disruption connectivity (measured as the fraction of node pairs that remain reachable). From a managerial standpoint, this implies that the majority of supply routes remain operational under moderate random disruption; however, this aggregate measure obscures the tail risk associated with the removal of structurally critical nodes such as Trader-6, as evidenced by the 85% resilience drop in Simulation 227,527, presented in Table 6. The resilience score changes from 0 to 0.85, which is a significant range. Based on 256,000 Monte Carlo simulations, the probability density function of resilience scores was plotted for risk assessment and presented in Figure 6.

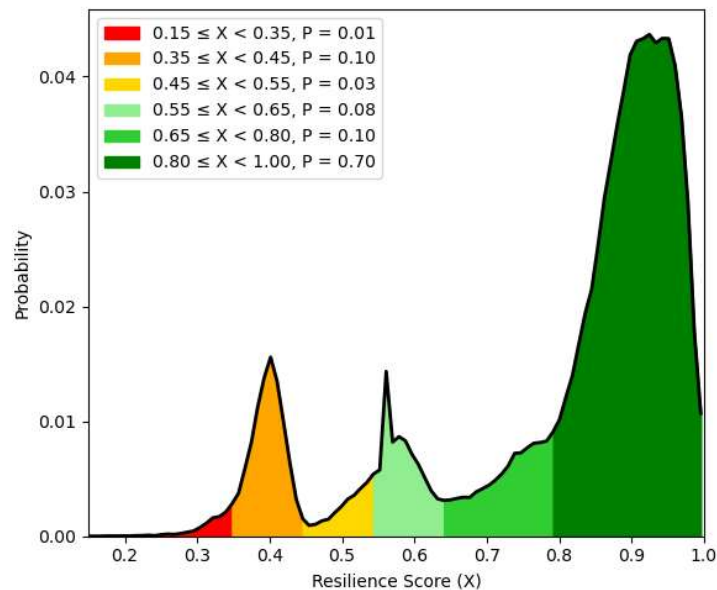


Figure 6. Probability density function of the resilience score.

In Figure 6, the risk areas were determined using an improved version of the natural break classification method. The figure illustrates five risk areas, ranging from the high-risk (maximum disruption) area, denoted in red, to the optimal performance (minimum disruption) area, denoted in dark green. According to Figure 6, the probability of having the maximum disruption for this supply chain network is 0.01. In this red area, the Drill Pipe Buying Company loses its connections to the raw material sources, which are represented by cylindrical nodes in Figure 3. On the other hand, the probability of performing in the optimum performance area for this supply chain network is 0.70. In the dark green area, even though there may be some disruptions, the Drill Pipe Buying Company can maintain a continuous supply flow, which means the disruptions will not be felt by the company but by intermediaries in the supply chain network. Therefore, Figure 6 indicates that the supply chain network of the Drill Pipe Buying Company has a significantly low risk of maximum disruption, with a probability of 0.01, while it has a high tendency to operate in the optimal performance area, with a probability of 0.70.

Table 7 shows the node group that resulted in the greatest change in the resilience score, which is a drastic drop with an 85% decrease in the resilience score. The main result of this drastic decrease is that the removed nodes, including Trader-6, are also removed, which is the most critical node in this supply chain network. By removing the Trader-6, the network loses its bridge for the node connectivity and its reach efficiency. Therefore, this decrease demonstrates the most destructive disruption in the network, and the final version of the supply chain network after this disruption is illustrated in Figure 7.

Table 7. The node group removal with the highest decrease in the resilience score.

Simulation	Resiliency Decrease	Removed Nodes
227527	0.85	- Chromium Mine-21 - EAF-7 - Manufacturer-22, Manufacturer-23 - Mining Company-1 - Scrap Supply-2 - Subsidiary-8, - Trader-6, Trader-12, Trader-17, Trader-19

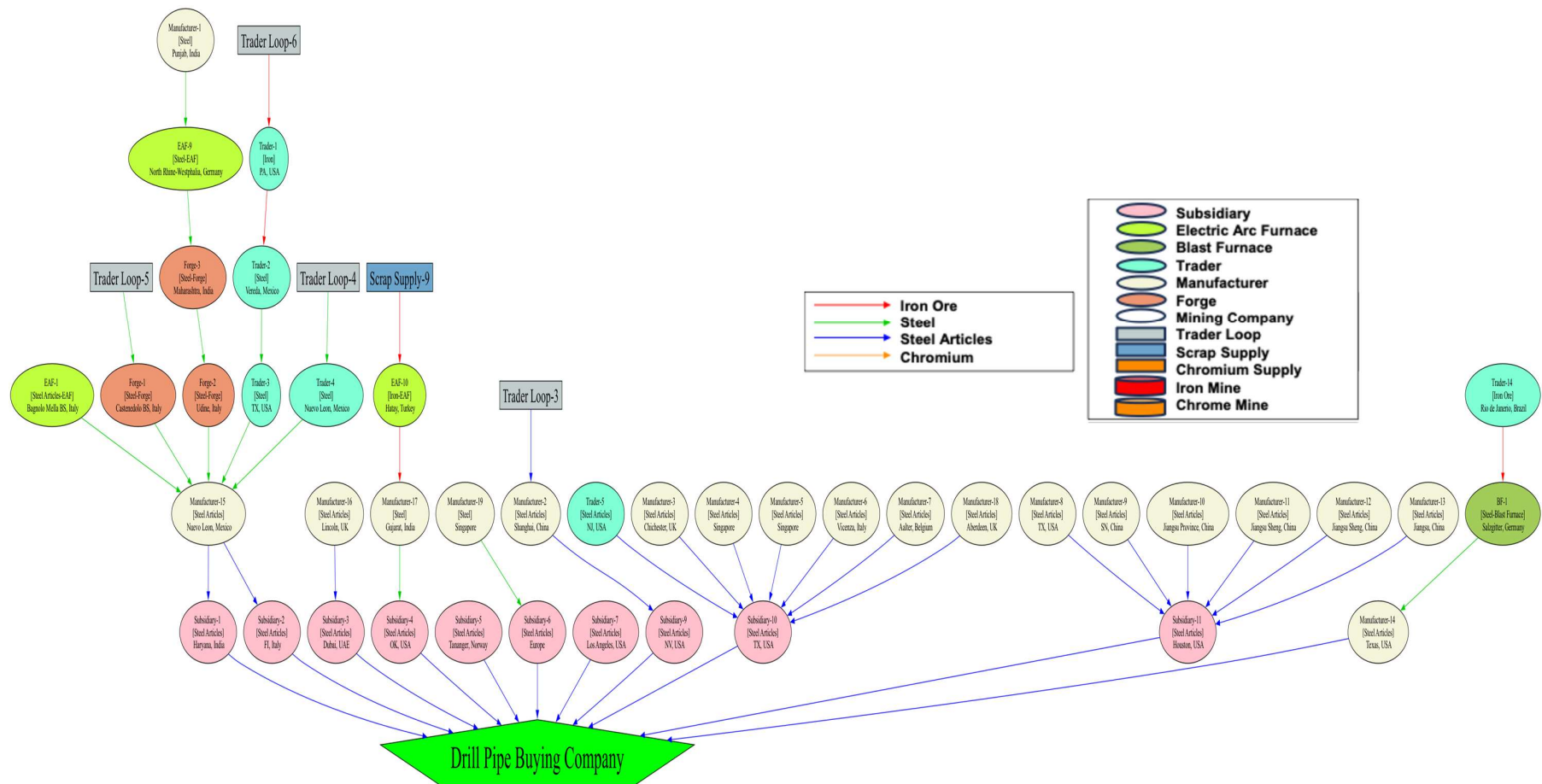


Figure 7. End-to-end supply chain network after the most destructive disruption scenario (simulation 227,527, 85% resilience drop). In direct visual contrast with Figure 3, the post-disruption network retains only 0 iron mine node(s), 0 chromium mine node(s), and 4 furnace node(s), with the majority of raw material access lost. The only verified raw material source remaining is Scrap Supply-9.

As shown in Figure 7, after the disruption of the nodes in Table 7 applied to Figure 3, the initial end-to-end supply chain network loses its access to chromium and iron ore mines, which jeopardizes the continuous supply of the Drill Pipe Buying Company. Moreover, the network loses its transparency. After the disruption, the only verified material source of this system is the Scrap Supply-9. By using this branch, drill pipe production can be continued; however, the supply will be insufficient for the Drill Pipe Buying Company's needs. Furthermore, the remaining nodes of Figure 7 can be classified as non-transparent nodes, and their access to raw material sources remains questionable.

According to the centrality analysis stated in Table 6 and the network topology presented in Figure 3, the stability of this network is highly dependent on Trader-6. Trader-6 is extremely critical because it provides the only path to the chromium mines and the majority of the iron mines, which can be followed in Figure 3. Disruption in this node results in losing connection to those mines as represented in Figure 7. Therefore, to increase the resiliency of this supply chain network, Drill Pipe Buying Company can increase the redundancy around Trader-6 and establish some backup trade connections in case of a disruption in Trader-6. Moreover, Drill Pipe Buying Company can create direct connections with the manufacturer and remove intermediary companies, such as traders.

Overall, the performed analysis underlines the structural robustness of the supply chain and the vital role of Trader-6 in preserving connectivity, efficiency, and transparency. Trader-6 is consistently identified as the most critical node by all centrality metrics, underlining its importance in connecting and serving as a leading player within the network. Stress testing using Monte Carlo simulations yields an average resilience score of 0.80 across 256,000 simulations, which is indicative of moderate overall resilience while at the same time revealing vulnerabilities in the network. Although the supply chain network of the Drill Pipe Buying Company has a high tendency to perform with optimum performance, as stated by 0.70 probability, the removal of a node group including the node Trader-6, during the stress testing caused a drastic drop of 85% in resiliency, leading to the disconnection of key raw material sources, such as chromium and iron mines, which would disrupt the supply chain. The results pinpoint that there is too much dependence on a single node within the network. It shows that increasing redundancy about Trader-6 is essential and should also be directly linked to manufacturers to reduce dependence on intermediaries. Implementing such strategies could significantly enhance supply chain robustness, transparency, and responsiveness against disruptions.

5. Conclusions

Several methodological constraints should be noted when interpreting these findings. First, the analysis is based on a single anonymized case study; while the methodology is designed to be generalizable, transferability to other commodity chains and industry contexts has not been empirically validated. Second, the proprietary trade data exhibit country-level reporting biases that systematically undercount supply chain branches in jurisdictions with low disclosure. Third, transparency classifications are based on observed trade links and do not incorporate audited or third-party verified supply chain data; as such, they represent a data-driven approximation rather than a verified ground truth. Fourth, resilience scores derived from Monte Carlo simulations are sensitive to the network topology at the time of data collection and may not reflect dynamic changes in supply chain structure. Additionally, the current study employs a single disruption intensity (10% node removal); future work will include sensitivity analyses at alternative disruption probabilities to verify the robustness of the critical node identification.

The research introduces an innovative methodology for tracing and analyzing the supply chain network for the Cr-13 Steel Drill Pipes. The entire framework presents a holistic view of the structure and dynamics of this supply chain, using proprietary global

trade transaction data and Harmonized System (HS) codes, which map every stage of this supply chain from end-user to raw material sources. The resulting mapping has provided granular insight into the flow of materials and complex interdependencies in the network of entities' roles. This is a far more detailed supply chain mapping exercise, made possible by combining Python 3.9 with the dot language and advanced graph analytics, helping to expose critical nodes, complexities, and areas of vulnerability characteristic of the supply chain network.

Beyond tracing product movement, the methodology offers a systematic classification of key stakeholders, such as subsidiaries, traders, manufacturers, and mining companies, based on their functional roles within the supply chain. Advanced graph analysis techniques, including giant connected component analysis, degree centrality, betweenness centrality, closeness centrality, and eigenvector centrality, were applied to identify the most critical nodes. These techniques revealed essential elements necessary for maintaining the efficiency, robustness, and connectivity of the supply chain. A pivotal innovation in this study is the introduction of the traceable transparency method, which classifies supply chain branches into four distinct categories: fully transparent, highly transparent, moderately transparent, and non-transparent. This categorization provides stakeholders with a clear understanding of visibility across the supply chain, helping to pinpoint specific risks and prioritize areas for transparency improvement.

An important contribution of this study is that it aligns with the increasing imperative for sustainable supply chain management. Even though the present analysis focuses on structural and operational dimensions, the methodology developed here will pave the way for integrating environmental dimensions, for instance, GHG emissions data, into supply chain analysis. This would help industries in the identification of high-emission nodes and implement strategies to reduce their emissions in line with global efforts to support climate initiatives, like the Paris Agreement. For example, identifying and optimizing high-emission segments could allow companies to lower their carbon footprint, comply with evolving carbon-related regulations, and lower associated costs such as carbon taxes. The traceability framework proposed in this study provides a practical roadmap for industries to transition toward greener operations, enhancing their corporate sustainability profiles and thereby helping to achieve global emission-reduction targets.

The study also highlights the importance of resilience in global supply chains, especially in an era characterized by increasing complexity and vulnerability to disruptions. Through the application of graph analytics and stress testing using Monte Carlo simulations, the research revealed that specific nodes, such as Trader-6, serve as critical points of connectivity and stability. Disruptions at these nodes can have cascading effects, significantly impairing the functionality and transparency of the entire network. The findings emphasize the need for redundancy and contingency planning to mitigate such risks. For instance, establishing direct connections to manufacturers and disintermediating certain traders could not only strengthen resilience but also improve efficiency and reduce costs.

The implementation of the methodology for the Cr-13 Steel Drill Pipes revealed that the use of scrap material epitomizes sustainability through recycling within the supply chain, aligning with global efforts to lessen environmental impacts and usher in a circular economy. The integration of scrap material, however, opens up issues of traceability and transparency within the supply chain. Supply chains for scrap materials can be very complex and usually have a lower degree of regulation, leading to a lack of clarity with regard to the provenance and quality of these materials. Such ambiguity can pose significant hurdles in ensuring conformity with environmental and quality standards.

Transparency is vital in this regard. Increased transparency in the use of scraps would improve traceability, strengthen adherence to sustainability standards, and enhance supply chain resilience by mitigating the risk of supply and quality disruptions.

This resilience further helps to support transparency through the reinforcement of systems that maintain sufficient strength to maintain operational visibility, even in the face of disruption. Consequently, initiatives to enhance traceability and transparency within scrap material supply chains are crucial for strengthening both sustainability and resilience. These efforts are vital in guaranteeing that recycled materials yield beneficial effects on the supply chain while upholding operational and environmental standards.

This work represents a significant advancement in supply chain analysis, addressing key challenges in transparency, sustainability, and the resilience of supply chain networks. Furthermore, it provides industries with a data-driven approach to optimize supply chain management, ensuring compliance with regulatory standards, meeting consumer demands for ethical and sustainable sourcing, and enhancing operational efficiency. Although the current application of the methodology was made to Cr-13 Steel Drill Pipes, the methodology is versatile and scalable, making it applicable to a wide range of industries and products.

Future research priorities include the following: (1) integrating firm-level GHG emission data to enable Scope 3 quantification alongside structural transparency assessment; (2) validating the traceable transparency classification against audited supply chain records from certified sources such as LBMA and RJC; (3) applying the methodology to additional commodity chains such as cobalt and lithium to test cross-industry generalizability; (4) extending the Monte Carlo framework to incorporate dynamic disruption scenarios reflecting geopolitical shocks or regulatory changes; and (5) integrating real-time tracking data and advanced machine learning algorithms to capture the dynamic nature of supply chains, enabling proactive risk management and targeted interventions to reduce emissions. As global supply chains become increasingly intertwined with both economic and environmental systems, this study provides a practical tool for exploring their complexities and driving their evolution toward more resilient, transparent, and sustainable trade networks.

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References

1. Emrouznejad, A.; Abbasi, S.; Sıcakyüz, Ç. Supply chain risk management: A content analysis-based review of existing and emerging topics. *Supply Chain Anal.* **2023**, *3*, 100031. <https://doi.org/10.1016/j.sca.2023.100031>.
2. Esan, O.; Ajayi, F.A.; Olawale, O. Supply chain integrating sustainability and ethics: Strategies for modern supply chain management. *World J. Adv. Res. Rev.* **2024**, *22*, 1930–1953. <https://doi.org/10.30574/wjarr.2024.22.1.1259>.
3. Guo, Y.; Liu, F.; Song, J.-S.; Wang, S. Supply chain resilience: A review from the inventory management perspective. *Fundam. Res.* **2024**, *5*, 450–463. <https://doi.org/10.1016/j.fmre.2024.08.002>.
4. Katsaliaki, K.; Galetsi, P.; Kumar, S. Supply chain disruptions and resilience: A major review and future research agenda. *Ann. Oper. Res.* **2022**, *319*, 965–1002. <https://doi.org/10.1007/s10479-020-03912-1>.
5. Jestratijevic, I.; Uanhoro, J.O.; Rana, M.R.I. Transparency of sustainability disclosures among luxury and mass-market fashion brands: Longitudinal approach. *J. Clean. Prod.* **2024**, *436*, 140481. <https://doi.org/10.1016/j.jclepro.2023.140481>.

6. Chen, J.-Y. Responsible sourcing and supply chain traceability. *Int. J. Prod. Econ.* **2022**, *248*, 108462. <https://doi.org/10.1016/j.ijpe.2022.108462>.
7. Wren, B. Sustainable supply chain management in the fast fashion Industry: A comparative study of current efforts and best practices to address the climate crisis. *Clean. Logist. Supply Chain* **2022**, *4*, 100032. <https://doi.org/10.1016/j.clscn.2022.100032>.
8. Rissman, J.; Bataille, C.; Masanet, E.; Aden, N.; Morrow, W.R.; Zhou, N.; Elliott, N.; Dell, R.; Heeren, N.; Huckestein, B.; et al. Technologies and policies to decarbonize global industry: Review and assessment of mitigation drivers through 2070. *Appl. Energy* **2020**, *266*, 114848. <https://doi.org/10.1016/j.apenergy.2020.114848>.
9. André, P.; Pirlot, A. When Are Carbon Border Adjustment Measures Just? *Polit. Stud.* **2024**, *73*, 305–325. <https://doi.org/10.1177/00323217241238125>.
10. Jush, G.K.; Elliott, J.; Foster, I.; Kortum, S.; Minson, T. Chicago Unbound Chicago Unbound Unilateral Carbon Taxes, Border Tax Adjustments, and Carbon Unilateral Carbon Taxes, Border Tax Adjustments, and Carbon Leakage Leakage Recommended Citation Recommended Citation. Available online: https://chicagounbound.uchicago.edu/law_and_economics (accessed on 4 April 2024).
11. Chandramohan, J.; Chakravarthi, R.P.A.; Ramasamy, U. A comprehensive inventory management system for non-instantaneous deteriorating items in supplier- retailer-customer supply chains. *Supply Chain Anal.* **2023**, *3*, 100015. <https://doi.org/10.1016/j.sca.2023.100015>.
12. Bellora, C.; Fontagné, L. EU in search of a Carbon Border Adjustment Mechanism. *Energy Econ.* **2023**, *123*, 106673. <https://doi.org/10.1016/j.eneco.2023.106673>.
13. Povitkina, M.; Jagers, S.C.; Matti, S.; Martinsson, J. Why are carbon taxes unfair? Disentangling public perceptions of fairness. *Glob. Environ. Change* **2021**, *70*, 102356. <https://doi.org/10.1016/j.gloenvcha.2021.102356>.
14. Tost, M.; Murguia, D.; Hitch, M.; Lutter, S.; Luckeneder, S.; Feiel, S.; Moser, P. Carbon prices for meeting the Paris Agreement and their impact on key metals. *Extr. Ind. Soc.* **2020**, *7*, 471–481. <https://doi.org/10.1016/j.exis.2020.01.012>.
15. Alnogaïdan, M. Block-chain for Sustainability: Tracing Environmental Impacts in Supply Chains. *Green Environ. Technol.* **2024**, *1*, 12–22.
16. Raimi, M.O.; Saliu, A.O.; Babatunde, A.; Okon, O.G.; Taiwo, P.A.; Ahmed, A.K.; Loto, O.; Iyingiala, A.A.; Telu, M. The Challenges and Conservation Strategies of Biodiversity: The Role of Government and Non-Governmental Organization for Action and Results on the Ground. In *Biodiversity in Africa: Potentials, Threats and Conservation*; Springer: Singapore, 2022; pp. 473–504. https://doi.org/10.1007/978-981-19-3326-4_18.
17. Kong, N.; Salzmann, O.; Steger, U.; Ionescu-Somers, A. Moving Business/Industry Towards Sustainable Consumption. *Eur. Manag. J.* **2002**, *20*, 109–127. [https://doi.org/10.1016/S0263-2373\(02\)00022-1](https://doi.org/10.1016/S0263-2373(02)00022-1).
18. Zhu, Q.; Lai, K. Enhancing supply chain operations with extended corporate social responsibility practices by multinational enterprises: Social capital perspective from Chinese suppliers. *Int. J. Prod. Econ.* **2019**, *213*, 1–12. <https://doi.org/10.1016/j.ijpe.2019.02.012>.
19. Dwivedi, Y.K.; Hughes, L.; Kar, A.K.; Baabdullah, A.M.; Grover, P.; Abbas, R.; Andreini, D.; Abumoghli, I.; Barlette, Y.; Bunker, D.; et al. Climate change and COP26: Are digital technologies and information management part of the problem or the solution? An editorial reflection and call to action. *Int. J. Inf. Manage.* **2022**, *63*, 102456. <https://doi.org/10.1016/j.ijinfomgt.2021.102456>.
20. Lambrechts, W. Ethical and Sustainable Sourcing: Towards Strategic and Holistic Sustainable Supply Chain Management. In *Decent Work and Economic Growth*; Springer, Cham, Switzerland, 2020; pp. 1–13. https://doi.org/10.1007/978-3-319-71058-7_11-1.
21. Jamil, M.A.; Mustofa, R.; Hossain, N.U.I.; Rahman, S.M.A.; Chowdhury, S. A structural equation modeling framework for exploring the industry 5.0 and sustainable supply chain determinants. *Supply Chain Anal.* **2024**, *6*, 100060. <https://doi.org/10.1016/j.sca.2024.100060>.
22. Feasley, A. Eliminating Corporate Exploitation: Examining Accountability Regimes as Means to Eradicate Forced Labor from Supply Chains. *J. Hum. Traffick.* **2016**, *2*, 15–31. <https://doi.org/10.1080/23322705.2016.1137194>.
23. Bhandari, N.; Garza-Reyes, J.A.; Rocha-Lona, L.; Kumar, A.; Naz, F.; Joshi, R. Barriers to sustainable sourcing in the apparel and fashion luxury industry. *Sustain. Prod. Consum.* **2022**, *31*, 220–235. <https://doi.org/10.1016/j.spc.2022.02.007>.
24. Şen, A. The US fashion industry: A supply chain review. *Int. J. Prod. Econ.* **2008**, *114*, 571–593. <https://doi.org/10.1016/j.ijpe.2007.05.022>.
25. Kügerl, M.-T.; Hitch, M.; Gugerell, K. Driving factors for responsible sourcing in Europe: Motivations of renewable energy technology manufacturers. *Extr. Ind. Soc.* **2025**, *23*, 101649. <https://doi.org/10.1016/j.exis.2025.101649>.
26. Cariou, P.; Parola, F.; Notteboom, T. Towards low carbon global supply chains: A multi-trade analysis of CO2 emission reductions in container shipping. *Int. J. Prod. Econ.* **2019**, *208*, 17–28. <https://doi.org/10.1016/j.ijpe.2018.11.016>.

27. Lähdeaho, O.; Hilmola, O.-P. An exploration of quantitative models and algorithms for vehicle routing optimization and traveling salesman problems. *Supply Chain Anal.* **2024**, *5*, 100056. <https://doi.org/10.1016/j.sca.2023.100056>.
28. Sodhi, M.S.; Tang, C.S. Research Opportunities in Supply Chain Transparency. *Prod. Oper. Manag.* **2019**, *28*, 2946–2959. <https://doi.org/10.1111/poms.13115>.
29. Hitch, M.; Wood, R.J.; Barakos, G.; Schinckus, C. Copper, crime, and the circular economy: How shadow flows threaten the green economy. *Extr. Ind. Soc.* **2026**, *26*, 101875. <https://doi.org/10.1016/j.exis.2026.101875>.
30. Sonar, H.; Sarkar, B.D.; Joshi, P.; Ghag, N.; Choubey, V.; Jagtap, S. Navigating barriers to reverse logistics adoption in circular economy: An integrated approach for sustainable development. *Clean. Logist. Supply Chain* **2024**, *12*, 100165. <https://doi.org/10.1016/j.clscn.2024.100165>.
31. Grafström, J.; Aasma, S. Breaking circular economy barriers. *J. Clean. Prod.* **2021**, *292*, 126002. <https://doi.org/10.1016/j.jclepro.2021.126002>.
32. Calvão, F.; Archer, M. Digital extraction: Blockchain traceability in mineral supply chains. *Polit. Geogr.* **2021**, *87*, 102381. <https://doi.org/10.1016/j.polgeo.2021.102381>.
33. Barros, M.V.; Salvador, R.; do Prado, G.F.; de Francisco, A.C.; Piekarski, C.M. Circular economy as a driver to sustainable businesses. *Clean. Environ. Syst.* **2021**, *2*, 100006. <https://doi.org/10.1016/j.cesys.2020.100006>.
34. Hellweg, S.; Canals, L.M.I. Emerging approaches, challenges and opportunities in life cycle assessment. *Science* **2014**, *344*, 1109–1113. <https://doi.org/10.1126/science.1248361>.
35. Hertwich, E. *Assessing the Environmental Impacts of Consumption and Production: Priority Products and Materials*; United Nations Environment Programme (UNEP): Nairobi, Kenya, 2010.
36. Odulaja, B.A.; Oke, T.T.; Eleogu, T.; Abdul, A.A.; Daraojimba, H.O. Resilience in the Face of Uncertainty: A Review on the Impact of Supply Chain Volatility Amid Ongoing Geopolitical Disruptions. *Int. J. Appl. Res. Soc. Sci.* **2023**, *5*, 463–486. <https://doi.org/10.51594/ijarss.v5i10.634>.
37. Ogunsoto, O.V.; Olivares-Aguila, J.; ElMaraghy, W. A conceptual digital twin framework for supply chain recovery and resilience. *Supply Chain Anal.* **2025**, *9*, 100091. <https://doi.org/10.1016/j.sca.2024.100091>.
38. Aldrighetti, R.; Battini, D.; Ivanov, D.; Zennaro, I. Costs of resilience and disruptions in supply chain network design models: A review and future research directions. *Int. J. Prod. Econ.* **2021**, *235*, 108103. <https://doi.org/10.1016/j.ijpe.2021.108103>.
39. Pettit, T.J.; Croxton, K.L.; Fiksel, J. Ensuring Supply Chain Resilience: Development and Implementation of an Assessment Tool. *J. Bus. Logist.* **2013**, *34*, 46–76. <https://doi.org/10.1111/jbl.12009>.
40. Gardner, T.A.; Benzie, M.; Börner, J.; Dawkins, E.; Fick, S.; Garrett, R.; Godar, J.; Grimard, A.; Lake, S.; Larsen, R.K.; et al. Transparency and sustainability in global commodity supply chains. *World Dev.* **2019**, *121*, 163–177. <https://doi.org/10.1016/j.worlddev.2018.05.025>.
41. (Nel) Wognum, P.M.; Bremmers, H.; Trienekens, J.H.; van der Vorst, J.G.A.J.; Bloemhof, J.M. Systems for sustainability and transparency of food supply chains—Current status and challenges. *Adv. Eng. Inform.* **2011**, *25*, 65–76. <https://doi.org/10.1016/j.aei.2010.06.001>.
42. D’Adamo, I.; Gastaldi, M.; Giacalone, R.; Kazancoglu, Y. A strategic and social analytics model for sustainable packaging in the cosmetic industry. *Supply Chain Anal.* **2024**, *8*, 100090. <https://doi.org/10.1016/j.sca.2024.100090>.
43. Mboga, J. Ethical Sourcing to Ensure Sustainability in the Food and Beverage Industry and Eliciting Millennial Perspectives. *Eur. J. Econ. Financ. Res.* **2017**, *2*, p. 98. <https://doi.org/10.5281/zenodo.1009174>.
44. Ivanov, D.; Dolgui, A. A digital supply chain twin for managing the disruption risks and resilience in the era of Industry 4.0. *Prod. Plan. Control* **2021**, *32*, 775–788. <https://doi.org/10.1080/09537287.2020.1768450>.
45. Christopher, M.; Peck, H. Building the Resilient Supply Chain. *Int. J. Logist. Manag.* **2004**, *15*, 1–14. <https://doi.org/10.1108/09574090410700275>.
46. Aydin, N.Y.; Duzgun, H.S.; Heinemann, H.R.; Wenzel, F.; Gnyawali, K.R. Framework for improving the resilience and recovery of transportation networks under geohazard risks. *Int. J. Disaster Risk Reduct.* **2018**, *31*, 832–843. <https://doi.org/10.1016/j.ijdrr.2018.07.022>.
47. Saka, U.M.; Duzgun, S.; Bazilian, M.D. Analysis of world trade data with machine learning to enhance policies of mineral supply chain transparency. *Resour. Policy* **2024**, *89*, 104671. <https://doi.org/10.1016/j.resourpol.2024.104671>.
48. Marshall, D.; McCarthy, L.; Heavey, C.; McGrath, P. Environmental and social supply chain management sustainability practices: Construct development and measurement. *Prod. Plan. Control* **2015**, *26*, 673–690. <https://doi.org/10.1080/09537287.2014.963726>.

49. International Trade Administration U.S. Department of Commerce. Understanding HS Codes and the Schedule B. Harmonized System (HS) Codes. Available online: <https://www.trade.gov/harmonized-system-hs-codes#:~:text=Among%20classification%20systems%2C%20Harmonized%20System,method%20of%20classifying%20traded%20products> (accessed on 13 September 2024).
50. United States International Trade Commission. Harmonized Tariff Schedule. Available online: <https://hts.usitc.gov/> (accessed on 13 September 2024).
51. Aydogdu, K.; Duzgun, S. Emission Impacts of Direct Reduced Iron-Ore Processing Systems: A Systems Thinking Approach in Case Studies of Canada and Peru. *Steel Res. Int.* **2024**, *96*, 2400450. <https://doi.org/10.1002/srin.202400450>.
52. Bhore, S. Paris Agreement on Climate Change: A Booster to Enable Sustainable Global Development and Beyond. *Int. J. Environ. Res. Public Health* **2016**, *13*, 1134. <https://doi.org/10.3390/ijerph13111134>.

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