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Assessing Risks in the U.S. Copper Supply Chain for Resilience Enhancement

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Abstract: The Defense Advanced Research Projects Agency (DARPA) endeavors to improve the technological and operational foundations critical to national security. A focal point within their Resilient Supply and Demand Network (RSDN) project is to proactively identify risks in critical supply chains to proactively implement solutions. This research paper will specifically address risk factors prevalent within the scope of the copper supply chain as copper is deemed a critical material in the context of the Department of Defense's technological and operational capabilities. Through this research, specific risk factors were identified within a series of use cases involving various diplomatic relations between global copper suppliers to determine the predicted impact these outcomes would have on the national copper supply. These findings help address a focal point within DARPA's RSDN initiative is the proactive identification and mitigation of risks within critical supply chains.

Keywords: Copper, Supply chain, Department of Defense, DARPA, Risk mitigation

1. Introduction

In recent years, experts have identified the reliability of the metal supply chain as a national security concern due to the important role it plays in energy distribution as well as military product development. The Department of Defense's (DoD) Fiscal Year 2023 Budget Request estimated that $276 billion will be invested in military space-based systems, maritime systems, aircraft and related systems, communication and computer systems, ground systems, and missiles and munitions (Office Under the Secretary of Defense Chief Financial Officer, 2023). Being that copper plays an integral role in construction and utility in future military systems, this indicates that soon there will be a significant increase in metal demand within the DoD.

Specifically, many munitions, electrical infrastructure, and various vehicle systems are heavily reliant on copper components. According to reports by the Institute for Defense Analyses for the Defense Logistics Agency, copper is the second most used material by weight in United States defense production (Wischer, Bazilian, and Amoah, 2023). As a result, copper faces skyrocketing demand amid United States arsenal restocking and defense vehicle manufacturing expansion. Thus, putting a greater strain on copper supply chain capabilities and pointing to the increasing likelihood of future copper delays and shortages.

Due to the DoD's expected increase in copper demand, it becomes necessary to ensure that the available supply options are reliable and that infrastructure is equipped to handle increased production and distribution. Research surrounding this topic revealed that ongoing supply chain disruptions and historically low inventories have resulted in supply deficits and delays (Moody's Analytics Service, 2023). These supply chain disruptions are due to a combination of risk factors that fall under the categories of political and regulatory, environmental, and social concerns. The researchers surveyed scientific literature, analyzed U.S. DoD documents, and conducted exploratory interviews with subject matter experts to synthesize information to help predict the future impacts of identified risk factors within the copper supply chain.

2. Copper Supply Chain Phases and Processes

A University of Arizona Superfund Research Center study on national copper production outlines the three primary phases of the copper supply chain: mining, refining, and manufacturing. Each phase involves intricate processes to transform copper ore into purified concentrations used in various Department of Defense (DoD) systems. The mining phase of the copper supply chain is complex due to the extensive effort required to select a mine, remove copper ore from the ground, test the concentration of copper within different batches of ore, and prepare it for the refinement process. At the end of this phase, random samples of the crushed gravel are tested to determine the average concentration of copper from a specific location of the mine as well as to ensure no nugget deficiencies exist (J. Donigan, personal communication with Moody’s Analytics, January 14, 2024).

Within the refinement phase, the copper ore undergoes a series of chemical reactions, which are dependent on the type of ore present, to extract copper components from other minerals in the compound (The University of Arizona Super Research Center, 2019). If the tests reveal that a batch of copper is oxide ore, then it will likely be processed using hydrometallurgy. Hydrometallurgy can be defined through three key phases: leaching, creating a solution concentration, and compound recovery. An aqueous solution leaches through the ore to separate unwanted compounds and produce a solution of copper sulfate with concentrations. An electrical current is run through this solution which separates the copper from the rest of the components resulting in a product of 99.99% pure copper (The University of Arizona Super Research Center, 2019). However, if initial testing reveals that a batch of copper is generally sulfide ore, pyrometallurgy will be used in the refinement process. Pyrometallurgy can be defined by three phases including froth floatation, smelting, and electrolysis. Within froth floatation, liquid is added to the copper ore where it is thoroughly mixed removing impurities and allowing solid ore particles to collect at the bottom. During the smelting step, these particles are dried and heated to 2300 degrees Fahrenheit helping to burn sulfide and iron off of the ore particles. The residual particles are placed into a tank full of electrolyte solution and an electric current is applied resulting in the positively charged copper ions plating the cathode and producing a product of 99.99% copper (The University of Arizona Super Research Center, 2019).

After the refinement phase, copper manufacturers mold the copper into pieces that support their products of interest in the manufacturing phase. As a result, it becomes hard to define a single manufacturing process for copper as the manufacturing phase involves specialization based on civilian or military use and the manufacturer of the refined copper. If refined copper is to be used for civilian products, refined copper is shipped to various civilian manufacturers and turned into electrical infrastructure, motors, generators, and construction materials (Copper Development Association Inc., 2022). From here, the produced products are shipped to trading firms, retail shops, or leasing companies where they are bought and employed, thus starting their active lifecycle (Sauer and Seuring, 2014). However, if refined copper is to be used for military products, it will be shipped to DoD manufacturers that specialize in munitions, weapon systems, vehicles, and infrastructure supporting electricity. Once these products are created, they are shipped to wholesale inventory management facilities that separate them into “Inter-Theatre” inventory or “Intra-theatre” inventory (Department of Logistics Agency, 2022). Depending on their assigned category, products will be shipped to military distribution depots which will help properly deliver them for use to DoD facilities across the country and the world (Officer of the Deputy Assistant Secretary of Defense Logistics, 2022).

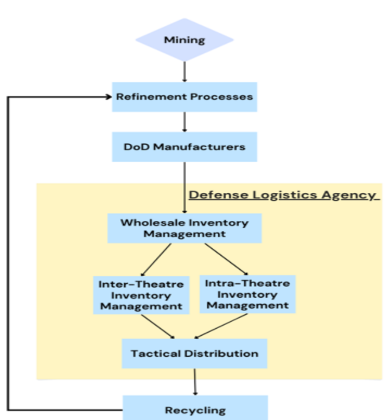

Figure 1. DoD Copper Supply Chain

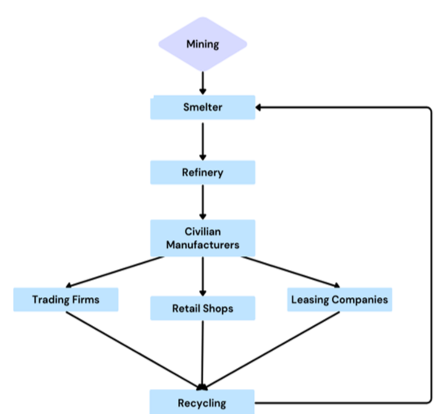

Figure 2: Civilian Copper Supply Chain

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3. Risk Factor Analysis

3.1 General Risk Categories

An essential component in comprehending copper supply chain dynamics is identifying risk factors affecting aggregate copper production (Table 1). Preliminary investigations have discerned significant risk elements within the three pivotal phases of the metal supply chain, encompassing political and regulatory, environmental, and social domains. Political and regulatory concerns include the lack of supplier diversification, compliance with worker safety regulations, and geopolitical relations. Currently, China accounts for a significant majority of global metal production with refining and smelting rates that have reached upward of 80% in some years (Chen, Xu, Yang, Zhang, 2022). This places a constraint on government officials to overlook worker safety violations and maintain positive foreign relations with countries that have significant control over metal production as poor relations can lead to a reduction in downstream metal supply as well as volatility in prices (Ceder, Fu, Gaustad, and Olivetti, 2017).

Environmental concerns encompass the ecological impact of mining activities and the disruptive risk weather events have within the metal supply chain. Due to limited supplier diversity in the international metal supply chain, a natural disaster in one of the primary metal-producing countries could damage infrastructure creating instability in metal supply and price (Hughes, 2021). Additionally, the United States enforces strict environmental standards within its mining and manufacturing industries. As an example, subject matter experts at the copper mine at Freeport-McMoRan, reported that compliance with the Clean Air Act and other regulatory measures have a significant impact on the cost of mining operations and continuous improvement (Freeport-McMoRan, 2024). As a result, we see the United States offshoring copper refinement to other regions with different compliance requirements, making this process significantly more economical than if it were to be completed domestically.

Social concerns encompass risks associated with limited domestic metal supply chain infrastructure and the costs of developing these capabilities. The United States is more than 58% net reliant on metal imports due to the lack of domestic infrastructure capabilities that support metal production (Riofrancos, 2023). After the COVID-19 pandemic exposed significant resilience and reliability issues in the foreign metal supply chain operations, there has been a recognition that this problem could be mitigated by increasing domestic infrastructure capabilities (Chen, Xu, Yang, Zhang, 2022). This will help reduce current risks involving corruption and lack of oversight in general metal supply chain operations due to the reliance on foreign suppliers.

Table 1. Defining Specific Copper Supply Chain Risk Factors

Risk Factor	Type	Definition
Supplier Worker Safety	Regulatory Social	The risk of the supplier failing to provide a safe working environment, exposing the organization to liabilities, loss of business reputation, and supply disruptions
Regulator Changes	Regulatory	The risk that the evolving regulatory landscape will increase the likelihood and impact of regulatory noncompliance for suppliers and contracts
Trade and Tariffs	Political Regulatory	The risk that uncertain or unfavorable trade regulations will result in operational inefficiencies or financial losses
Supplier Geo-political	Political Social	The risk that political, economic, and social volatility in relevant geographies will adversely affect supplier operations and performance
Supply Concentration	Political Social	The risk based on the concentration of product within one supplier within a category or business line versus the supply market concentration
Labor Laws	Regulatory Social	The risk that the supplier fails to comply with applicable labor laws, resulting in financial losses and reputational damage
Environmental Regulations	Regulatory Environmental	The risk that inconsistent laws surrounding product supply chains disadvantage certain suppliers over others; risk of failing to comply with environmental regulations resulting in financial losses
Natural Disasters	Environmental	The risk that destructive events in nature damage critical infrastructure resulting in financial losses, reduced production, and delays
Quality	Regulatory	The risk that the supplier's products fail to meet adequate quality standards, potentially harming business performance and long-term customer loyalty

3.2 Risk Factor Source Identification

The authors obtained information regarding specific risk factors within the copper supply chain from an initial literature review as well as interviews with stakeholders and subject matter experts regarding copper supply chain operations. Table 2 identifies the specific sources that provided key information on the previously identified copper supply chain risk factors.

Table 2. Source Identification of Copper Supply Chain Risk Factors

		Risk Factors								
		Supplier Worker Safety	Regulator Changes	Trade and Tariffs	Supplier Geo-political	Supplier Concentration	Labor Laws	Environmental Regulations	Natural Disasters	Quality
Sources	1	**X**	**X**	**X**	**X**	**X**	**X**			**X**
	2	**X**		**X**		**X**		**X**	**X**	
	3	**X**			**X**		**X**	**X**		**X**
	4		**X**		**X**	**X**				
	5	**X**			**X**		**X**			
	6					**X**			**X**	
	7		**X**							**X**

1. Moody's Analytics Services, "Metals and Mining: Outlook Changes on Improving Business Conditions Despite Persistent Risks," [Unpublished Report].
2. Freeport-McMoRan, Presentation for the West Point team, [Unpublished Report].
3. Copper Development Association Inc., "U.S. Copper Supply and Consumption 2002 - 2022."
4. Chen, Xu, Yang, Zhang, "Global Supply Risk Assessment of the Metals Used in Clean Energy Technologies."
5. Ceder, Fu, Gaustad, and Olivetti, "Lithium-Ion Battery Supply Chain Considerations: Analysis of Potential Bottlenecks in Critical Metals."
6. Hughes, "The Stages of Mining: 5 Lifecycle Processes Explained."
7. Sun, "Supply Chain Risks of Critical Metals: Sources, Propagation, and Responses."

4. Use Case Analysis

Collaborators advised by government and industry subject matter experts converged on generalized versions of the following use cases for further analysis. These three primary use cases along with a baseline case were created to depict possible and influential future foreign relation realignments within the global copper supply chain network. In collaboration with DARPA scientists from the RSDN program, the authors identified three use cases that would address the risk of relying too heavily on obtaining copper from countries with varying geopolitical ties to the United States. The authors created a preliminary simulation of the use cases which integrated risk factors from the stakeholder analysis in addition to information gained from interviews with subject matter experts. Although this preliminary simulation relied on multiple stakeholder assumptions, the results help highlight current and future trends in the copper supply network regarding the United States' heavy reliance on Chile for copper supply and China's focus on controlling critical metal supply chains (Nakano, 2021). Comparing current copper supply levels and operations to these three use cases, the results can be analyzed to provide takeaways for risk mitigation strategies that would be most influential in ensuring a stable supply of copper for future DoD operations (Copper Development Association Inc., 2022). Table 3 further identifies the differences between each of the use cases and why their potential impacts are important.

Table 3. Use Case Explanations and Potential Impacts

Use Case	Explanation	Key Potential Impacts
Baseline	- No change in current copper supply chain operations - Provides a comparison for the extent to which other use cases impact the national copper supply	- Provide an understanding of current national copper supply trends
China Merger with Chile	- China expands its influence in the global copper supply market by merging with Chile - China would acquire control over Chile's copper companies and infrastructure	- Increased Chinese control over global copper trade - Higher tariffs on copper supplied to the United States from Chile - Greater chance of labor law and environmental violations in Chile
China Merger with All Copper Exporters to the U.S.	- China expands its influence in the global copper supply market by merging with all major copper-supplying countries - China would acquire control over these countries' copper companies and infrastructure	- Chinese domination within global copper trade - Higher tariffs on copper supplied to the United States from all major copper-supplying countries - Greater chance of labor law and environmental violations in major copper-supplying countries
China Merger with Chile with U.S. Risk Mitigation Strategies in Place	- China expands its influence in the global copper supply market by merging with Chile - China would acquire control over Chile's copper companies and infrastructure - The U.S. implements a suggested risk mitigation technique	- Demonstrate how risk mitigation efforts impact the national copper supply - Encourage emplacement of proactive mitigation strategies - Determine which mitigate strategy is the best option for the U.S. regarding reliance on foreign countries for copper supply

5. Conclusion and Future Research

The escalating demand for copper within the DoD exacerbates the strain on the copper supply chain, accentuating the need for reliable supply options and robust infrastructure capable of accommodating heightened production and distribution requirements. Current supply chain disruptions and historically low inventories have led to deficits and delays in copper supply. These disruptions are attributed to a combination of risk factors spanning political and regulatory, environmental, and social domains. This research helps establish an understanding of the distinct phases of the copper supply chain, the risks associated with each phase, and why these risks are important to consider when determining the reliability of the United States copper supply chain. The results of this research emphasize the importance of assessing the impact of various risk factors in ensuring the resilience of the copper supply chain.

Using the findings of this research, the authors created a preliminary simulation that weighted each of the risk factors based on their influence on copper production within the copper supply chain and then assigned a probability of each of these risks occurring within the provided use cases. The sum product of these values for each risk factor was calculated within the four use cases producing four risk scores. Using copper production and supply data over the past 20 years, the authors assigned risk scores to associated values of copper imports with a 95% confidence interval. The authors then simulated the U.S. copper imports of each use case over the next 20 years. The results of the simulation revealed that the use cases with higher risk scores (China Merger with All Copper Exporters to the U.S. and China Merger with Chile) produced significantly fewer amounts of copper import compared with the use cases with lower risk scores (Baseline and China Merger with Chile with U.S. Risk Mitigation Strategies in Place). Although these findings may seem intuitive, this methodology provides a way to quantify the extent to which key risk factors impact future copper supply chain imports and production.

Potential recommendations regarding the findings of this research involve implementing regulatory and policy strategies that mitigate geopolitical risk factors and increased funding towards enhancing the resilience of the copper supply chain through domestic infrastructure development. These strategies could catalyze regulatory adjustments to promote domestic refinement capabilities and reduce reliance on imported copper. An example of this would be adding copper to the USGS critical minerals list as it would underscore its importance within the nation's economy and technological domain. Additionally, this would encourage policymakers to advocate for regulatory adjustments to promote domestic refinement capabilities and decrease the nation's heavy reliance on refined copper imports. Strengthening trade and diplomatic ties with key copper-supplying nations may also mitigate the risk of supply disruptions and foster mutually beneficial relationships. On the international stage, fostering stronger trade and diplomatic ties with China may create a mutually beneficial relationship that mitigates the risk of potential conflict and reduces the risk of losing refined copper imports through competitive policy agreements with third parties.

Overall, recognizing the trend of the growing importance of copper to the United States highlights the need to either increase domestic production and refinement or mitigate risks to imports from key suppliers through diplomatic action with national competitors. DARPA and national security agencies can use this information to advocate for policy changes that promote domestic refinement production, reduce reliance on imported refined copper, and mitigate geopolitical risks by impacting the prioritization of diplomatic relations. If these findings are incorporated into strategic future planning, DARPA and national security agencies can act to mitigate risk to protect national security interests by ensuring a reliable supply of copper for future DoD operations.

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