THE INTEGRATION OF SYSTEMS ENGINEERING AND DATA ANALYTICS FOR ENHANCING THE RESILIENCY AND TRANSPARENCY OF MINERAL SUPPLY CHAINS

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Introduction

The International Energy Agency (IEA) reports that the average quantity of minerals required for the construction of new power generation capacity has increased by 50 percent since 2010; this coincides with the increasing proportion of renewable energy sources in overall capacity additions [1]. The transition to renewable energy requires a shift from a system that relies mainly on fuel to one that relies primarily on materials. For instance, electric vehicles require six times as much mineral input as conventional vehicles. Offshore wind farms require ten times the amount of minerals as gas-powered power plants [1]. To effectively mitigate global warming, it is crucial to prioritize a substantial increase in the production and supply of critical minerals. The surge in renewable technologies and infrastructure is both dramatic and necessary, as it aligns with the increasing demand for these sustainable solutions. Net-zero carbon targets are necessary due to the energy-intensive nature of mining, beneficiation, and metallurgical processes. The process of increasing decarbonization requires an increase in mining activities. According to the World Bank, the production of battery metals such as graphite, lithium, and cobalt must increase by nearly 500% by 2050 in order to satisfy the rising demand for renewable energy technologies [2]. Therefore, achieving a low-carbon future and fulfilling global warming mitigation objectives are significantly contingent upon establishing resilient and transparent mineral supply chains.

Mineral supply chains are complex sociotechnical systems, including social, economic, and technical dimensions, that require quantitative approaches to assessing their resiliency and transparency. A supply chain's resilience refers to its capacity to effectively anticipate and prepare for potential disruptions, effectively recover from any disruptions that occur, and successfully adapt to changes. The process of obtaining a mineral product typically commences with the extraction of minerals such as ores of gold, copper, iron, and coal from the earth through mining activities. Subsequently, the extracted rock undergoes various beneficiation processes to improve its mineral content, resulting in a concentrate. Metallurgical processes are then employed to extract the desired metal content from the concentrate. Finally, the obtained metal content is utilized in the production of various manufacturing products, such as jewelry, copper wire, and steel pipes. This production process involves flows of various materials (e.g., mercury and/or cyanide for gold doré, iron, chromite, and coal for stainless steel), which are traded and transported globally. The distribution of mineral resources is uneven, and this, along with variations in socio-political systems and geological factors, leads to distinct complexities in each mineral supply chain. Consequently, each mineral supply chain faces its own unique resiliency and transparency challenges.

Mineral Supply Chains Resiliency and Transparency

Steel is a significant engineering and construction material that is used in various settings in daily life, including in cars, ships, and energy infrastructures [3]. It is the industrial material with the most significant climate impact [3]. It accounted for about 8% of global greenhouse gas (GHG) emissions, with 2.6 billion tonnes of CO_2 [3] in 2020. Two main routes for steel production dominate the industry: the blast furnace-basic oxygen furnace (BF) route and the direct reduction iron (DRI) route. The two low-carbon steel-making processes are DRI and electric arc furnaces (EAF) using scrap. However, steelmaking using BF and DRI needs to be more sufficient to meet the demand for low-carbon steel. Iron ore and metallurgical coal are the two primary raw materials for steelmaking in BF and DRI. 98% of the iron ore is used in steelmaking. DRI steel production generally leads to lower GHG emissions than BF steel production. Both processes utilize iron ore as their primary raw material, but they respond differently to its properties, ultimately impacting the emissions produced. The BF method is capable of accommodating a diverse range of iron ore grades ranging between 56% to 64%. The inherent flexibility of both hematite (Fe_2O_3) and magnetite (Fe_3O_4) allows for their versatile use. On the other hand, the DRI process preferably accepts iron ore pellets with a grade of more than 67%. The grade criteria are necessitated by the fact that the DRI process does not include the smelting of iron ore pellets, hence preventing the separation of impurities into slag. The ore must thus be of high grade. The pellet reducibility, strength, and swelling criteria for DRI exhibit similarities to those seen in BF pellets. Consequently, the only differentiation between a BF pellet and a DRI pellet is in the disparity in ore quality. The iron ore supply with DRI grade is globally limited to seven iron ore mines. Considering that steel plays a crucial role in facilitating the

transition to a low-carbon economy, the transformation of the steel sector towards low-carbon steel production using DRI is constrained by global resource availability, which makes the low-carbon steel supply chain highly vulnerable.

Iron ore mining is one of the significant contributing commodities to the mining industry's total emissions, after coal and copper. Hence, there are significant efforts in net-zero carbon strategies developed by the largest iron ore mining companies. Considering that these companies` primary iron ore production is from surface mine operations, the significant GHG emissions in the mining operations are from the loading and hauling of iron ore. Therefore, efforts to reduce GHG emissions (i.e., low-carbon strategies) from iron ore mining should primarily focus on loading and hauling. Being a repetitive process, loading and hauling are considered ideal to be replaced with automated haulage systems (AHS) to generate significant benefits such as improved safety, productivity, repeatability, and reduced maintenance costs. In the last decade, large iron ore mining companies have increasingly adopted AHS as part of their low-carbon strategy. AHS is claimed to increase production and efficiency while decreasing diesel consumption and GHG emissions. Besides such claimed benefits, AHS and associated digital transformations are believed to significantly challenge the mining industry with broader social impacts on the workforce and communities, which may bring into question to what extent incorporating AHS into their fleet can enhance a company's contributions to sustainable development, especially the United Nations Sustainable Development Goals (SDGs). It is demonstrated that if mining companies only operate with conventional diesel fuels, AHS has higher overall haulage emissions per ton of material moved, yet significantly less non-productive emissions, highlighting the need for low-carbon transportation systems [4]. Although there are initiatives for net-zero haulage technologies like li-ion and hydrogen batteries they are also heavily dependent on mineral supply chains. Therefore, the interdependence of net-zero carbon strategies in mining systems on other mineral supply chains results in complex interconnected systems, decreasing the resilience of mineral supply chains.

Copper, which has recently been included on the list of critical minerals by the United States Department of Energy (DOE), has a narrow supply base problem like DRI-grade iron. 65% of documented copper resources are in only five countries: Chile, Australia, Peru, Mexico, and the US. The narrow supply base of copper can be attributed to various factors, including geological, historical, economic, and political reasons. Localized disruptions can affect global supply, such as a significant strike in Chile's mining sector or regulatory changes in Peru. In addition, the processing of copper ore and its subsequent concentrates need the use of sophisticated smelting techniques in order to transform it into a refined metal form (e.g., copper wire). With just three copper smelters now in operation, the United States, one of the major ore producers, has a limited domestic processing capacity. On the other hand, China has a far greater capability with the 14 copper smelters. China is also home to nine of the top 20 copper smelters. Hence, copper supply chains have significantly reduced resiliency due to the high level of interdependency on localized resources and smelters.

Unlike low-grade iron ores that can be processed via BF for steel making, copper does not exhibit a significant substitute in its supply chain. Although aluminum can be considered a substitute for copper, aluminum has 60% of copper's conductivity, which implies thicker aluminum wires to transfer the same amount of power. Additionally, aluminum may require additional insulation in some instances due to its lower heat conductivity. The absence of adequate alternatives for copper renders the supply chain highly vulnerable when faced with surges in demand.

Moreover, the process from the exploration and the first identification of a copper deposit to the commencement of production has a considerable duration, sometimes extending over many years or even decades due to permitting processes. The prolonged length of the permitting procedures presents a significant obstacle in efficiently increasing supply to satisfy sudden increases in demand. The inclusion of environmental, social, and governance (ESG) factors into mining operations, particularly the concept of social license to operate, introduces more intricacies to the sociotechnical framework of the supply chain.

The increased copper prices and advancement in extraction technology have led to the possibility of significant quantities of copper being present in older tailings. The use of novel extraction and processing methods has the potential to recover copper from previously uneconomical tailings. The potential of hydrometallurgical methods, namely bioleaching, in extracting copper from low-grade sources, including tailings, has been the subject of much investigation. The reprocessing of tailings has the potential to provide environmental benefits by mitigating the overall impact of waste material and reducing the related hazards linked to tailings storage. While tailings have the potential to address the need partially, they need to be more sufficient in satisfying the enormous global copper demands. Technological limitations in processing low-grade copper ores and tailings, along with lengthy permitting processes

and the need for social license to operate, contribute to delays in extracting existing and new resources to meet the surge in demand. In addition to the existing complexity, there has been a notable increase in artisanal small copper mining (ASCM) practice. The rise of ASCM might be attributed to the escalation of global copper prices and the extended permitting procedures. The prevalence of ASCM is mainly seen within the licensed area of large-scale mining corporations, leading to a contentious dynamic between local community-based artisanal miners and prominent multinational investors, therefore affecting their coexistence. Consequently, this rigidity and socio-environmental dynamics on the supply side hinder the copper supply chain's ability to be flexible, which is a crucial element of a resilient supply chain.

Concerns about the resilience of mineral supply chains are amplified by their opacity. Limited data and information sharing within the mineral supply chain exacerbates its opacity. Furthermore, the involvement of artisanal small-scale mining (ASM) in mineral supply chains contributes to the lack of transparency in the supply chain due to possible illicit activities [5]. Illicit operations effectively strengthen the resilience of the supply chain and render the transparency of the supply chain a challenging endeavor. The term "resilient" often has favorable implications; however, in this particular context, it pertains to the robustness and tenacity of a compromised system. When the supply chain is characterized by the pervasive presence of illicit activities and corruption, the eradication of these issues becomes a formidable task, resulting in a system that exhibits a high degree of resistance to change. Nevertheless, this particular manifestation of resilience is considered unfavorable. The mineral supply chain with ASM, despite its short-term efficacy, is deemed unsustainable in the long term due to the anticipated occurrence of legal disputes, reputational harm, and ESG issues.

While gold does not play a crucial role in the clean energy transition, the presence of a substantial amount of ASM in the supply chain enables us to examine the involvement of ASM in the supply chain of clean energy minerals such as tantalum, cobalt, and tin. Additionally, a closer look at the role of ASM in the gold supply chain reveals the distinctive characteristics that set mineral supply chains apart from other types of supply chains. Gold is one of the opaquest mineral supply chains due to traceability problems. 52% of the produced gold is used for jewelry making, 27% is sold as gold bars and coins, 11% is used for financial and central bank purposes, and 10% is used in the industry. On average, mining contributes to 70% of the annual gold supply, while the remaining portion is obtained through recycling [6]. The gold supply chain has interconnected tiers involved in the movement of gold, beginning with its extraction as ore from mines, followed by processing, transportation, refining, and ultimately reaching the market. The chain culminates with the ultimate customer, who receives either pure gold or an alloy.

Peru, the eighth-largest gold producer in the world and the largest gold producer in Latin America employs approximately 300,000 individuals [7]. While most miners operate informally, they typically work within legally designated mining areas. However, they need ownership of mining concessions and official mining permits from the state [8]. Due to legal uncertainties surrounding artisanal and small-scale mining (ASGM) and its prevalence in remote rural areas outside government jurisdiction, some ASGM operators may engage in selling gold to illicit actors who hold influential positions in gold supply chains. Additionally, these operators may face the risk of extortion by illicit actors, a phenomenon observed in other ASGM regions worldwide [9]. The convergence of the expanding ASGM industry, transnational organized crime, and corruption has had a detrimental impact on stability and security in numerous Latin American countries. These dynamics have global implications for security and governance [10]

Mineral Supply Chain Transparency and Resiliency Assessment Tool

The complex structure of mineral supply chains requires a comprehensive understanding of the socio-technical processes involved in order to improve their resilience and transparency. We developed a mineral supply chain transparency and resiliency tool that integrates systems engineering methods with machine learning approaches. The tool provides adaptive and scalable methods for unpacking each mineral supply chain's complex socio-technical system. It delivers a set of methods for investigating the mineral supply chains in two scales, namely local and global scales. On a global scale, the tool adopts supply chain analytics and delivers valuable insights into the worldwide trade of mineral commodities, including various forms such as concentrate, metal, scrap, and finished goods. The data on mineral supply chains reveals a significant disparity in trade, which is used as a relative measure of transparency. On the local scale, the tool incorporates the systems engineering methods, namely system dynamics models (SDM). The SDM approach examines the many components of the mineral supply chain, including its physical features, such as mining and beneficiation, as well as its sociotechnical characteristics, such as the workforce, regulatory factors, transportation modes, and other material flows. SDM allows one to comprehensively understand

the supply chain and assess its resiliency and transparency in its operations. Moreover, the quantification of the resilience of mineral supply chains can be achieved by the application of stressors to the SDM. In addition, explicit system models provide a quantitative evaluation of various decarbonization options throughout the whole supply chain.

Analysis of Mineral Supply Chains` Transparency in the Global Scale

We use machine learning (ML) techniques to examine trade discrepancies as a transparency measure. The information provided by the United Nations Comtrade includes comprehensive import and export statistics on a monthly and annual basis for about 200 countries and territories, which facilitates the adoption of ML methods. Our analysis includes over 50 million trade transactions involving more than 7000 commodities traded across over 200 countries over a span of 30 years. The analyses provide a metric that quantifies the relative level of transparency in the trade of mineral commodities. The aforementioned technology provides insights into the geographical and temporal variations in mineral supply networks on a global scale. Using ML-based technologies makes it feasible to assess the relative degree of transparency for different mineral supply chains. Figure 1 depicts the reporting performance of gold and steel commodities as a representative measure of supply chain transparency. The trade discrepancies seen in the proximity of the green and red zones shown in Figure 1 indicate supply chains with low and high degrees of transparency, respectively. The opaquest components of the supply chain, as seen in Figure 1, are gold concentrates, gold jewelry, and steel goods classified under HS Code 7206, which refers to nonalloy steel in ingots or other primary forms. We also used the tool to investigate relative transparency in battery materials supply chains: Natural graphite, magnesium, cobalt, lithium, and nickel. Additionally, we included two major battery products, lithium-ion batteries and primary cells and batteries with lithium, in the analyses. We found that trade of natural graphite, cobalt oxides and hydroxides, hydroxide, and peroxide of magnesium, lithium carbonate, lithium oxide and hydroxide, nickel oxides and hydroxides, nickel powders, and flakes are reported well with an acceptable trade discrepancy, indicating transparent supply chain components. On the other hand, cobalt ores and concentrates and primary cells and batteries with lithium are reported poorly, with significant trade discrepancies, demonstrating high opacity areas in the supply chain [11].
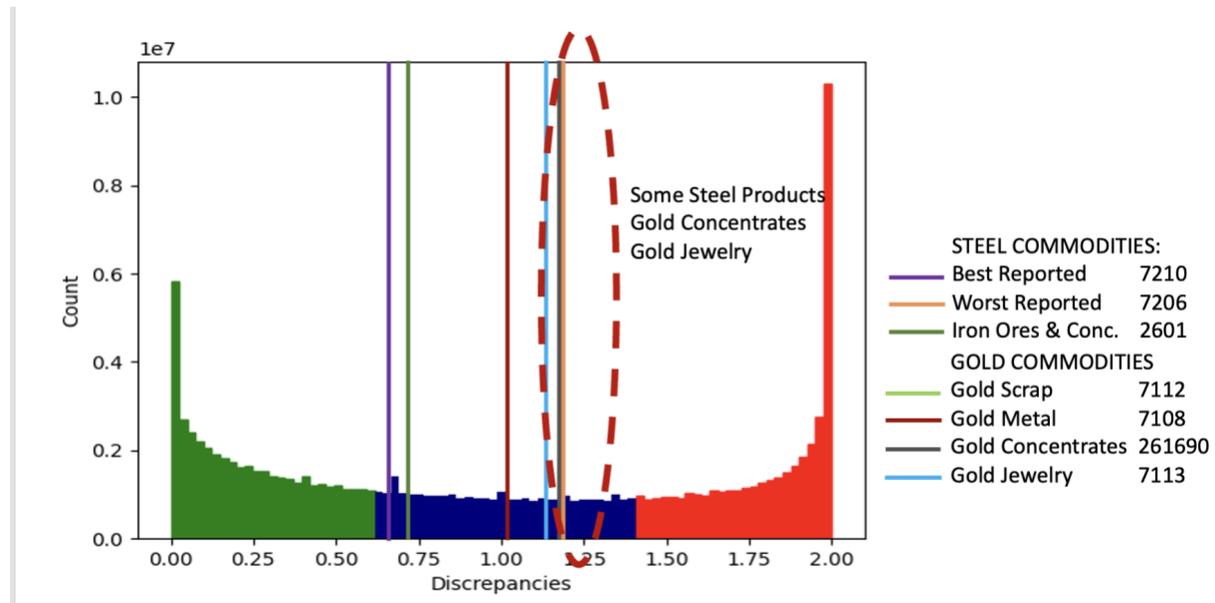

Figure 1. Relative trade discrepancy of steel and gold commodities as a proxy of transparency

Analysis of Mineral Supply Chains` Resiliency in the Local Scale

Our tool unpacks mineral supply chains using SDN. For example, we unpacked one of the opaquest mineral supply chains, ASGM, as an example for local scale application of the tool [5]. The ASGM supply chain typically starts at the gold mine, where the extraction of ore is carried out by a workforce and a range of equipment, including excavators for surface mines, pumps for alluvial mines, and explosives for hard rock mines. The ore that has been mined is transported to the mineral processing facility via trucks, rail carriages, or pipelines. Mineral processing plants exhibit variability depending on the type of ore and production technique employed. Nonetheless, the principal function of these plants is to enhance the gold grade of the run-of-mine (ROM) material through processes such as crushing, grinding, and other beneficiation methods. Subsequently, physical techniques such as gravity separation are employed to obtain a concentrated form of gold. These procedures need the use of a workforce, specialized machinery, and essential resources such as water and electricity. Following the implementation of physical mineral processing techniques, the concentrate undergoes a mixing procedure with mercury, facilitating the capture of gold particles by the mercury in the concentrate. The amalgam is formed as a consequence of the mixing procedure, whereby gold and mercury are combined. Subsequently, the amalgam is sold to the gold shop or processes at the site, where it undergoes combustion in order to eliminate the mercury by vaporization. Following the process of evaporation, the resulting combination is referred to as 'drone,' which has a gold content exceeding 90%. The doré, a semi-pure alloy of gold and other metals, is transported to the refinery facility. The doré undergoes a series of processes at the refinery to extract the pure gold. Once the refining process is complete, the refined gold is then dispersed to the market. The gold is made available for sale to various sorts of clients. A typical SDM of the described ASGM is illustrated in Figure 2.
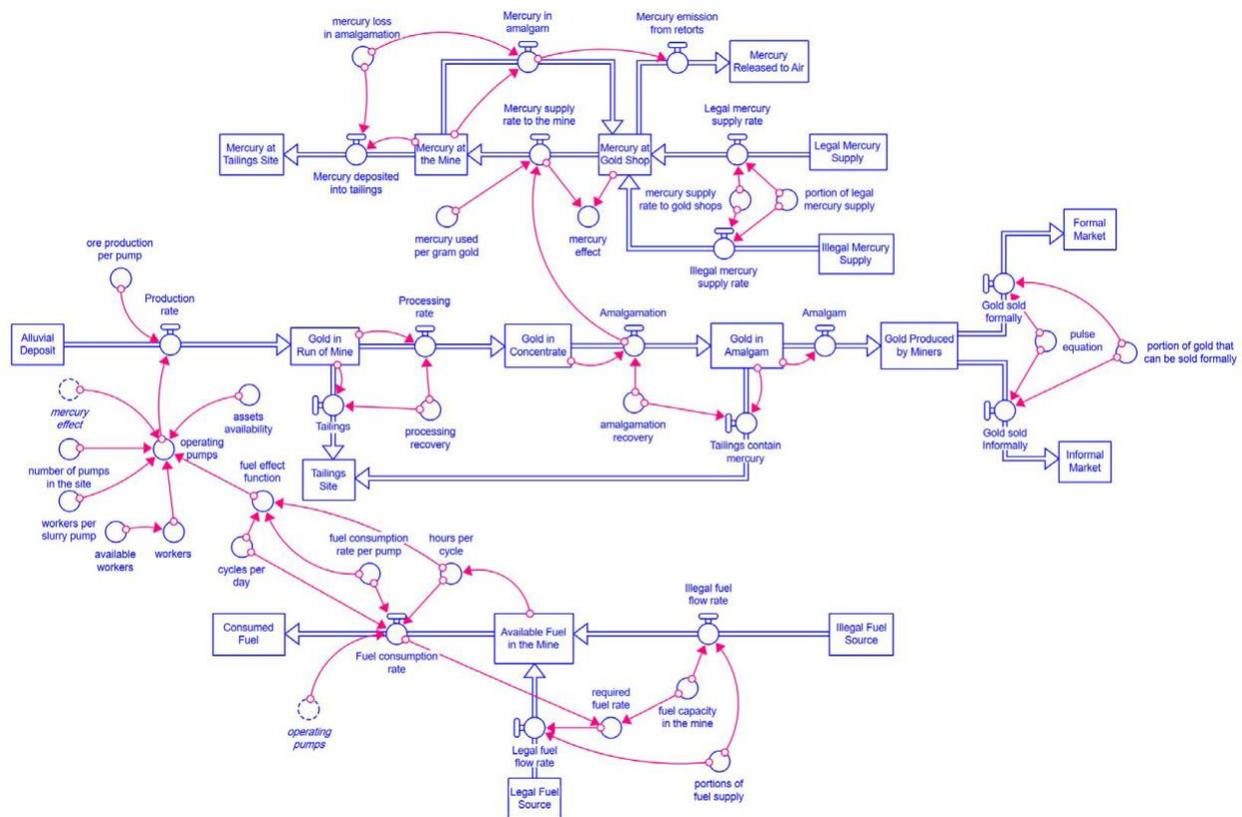

Figure 2. SDM for an ASGM [5].

The SDM of the ASGM activities in the Madre de Dios (MdD) region, situated in the Amazon rainforest and sharing borders with Bolivia and Brazil, provides quantitative insights into the local sale mineral supply chain. This area accounts for more than 70% of the informal gold production in Peru. With the SDM analysis, we found that a mere 5% of the overall mercury supply required for producing the claimed quantity of gold in MdD is obtained legally.

Even within the formal mining sector, there are instances when mercury is obtained illegally, above the legally permissible limits, in order to achieve desired levels of gold production. The SDM models revealed that ASGM in MdD releases 1.13 grams of mercury into the environment for every gram of gold produced. Furthermore, about 82% of this mercury is released into the air via the combustion of the amalgam during the production of doré. Our field data collection revealed that each ASGM mine owner is allowed to sell only 100 grams of gold to formal gold buyers per month, which makes the miners search for informal buyers to sell the rest of the produced gold.

Another example of the field scale analysis is the SDM we constructed to analyze emissions of a typical DRI-grade iron mine processing plant. The mine has an annual ore production of 35 million tons and produces iron concentrate of 6-18 million tons per year. We calculated the annual CO_2 emission of the processing plant as approximately 120,000 tons. The use of SDM offers a quantitative analysis of the supply chain system at the site level, including physical system components, material flows, and social and regulatory aspects.

Conclusions:

The transition to a low-carbon economy is crucial but a process that takes time and effort. The mineral supply chains that support this transition are complex and diverse. It is necessary to employ a combination of systems thinking, data analytics, multi-scale analyses, and broad collaboration between stakeholders. The ultimate objective is to establish a supply chain that can withstand unexpected disruptions and be transparent. Mineral supply chains exhibit high social, political, and environmental interdependency in various scales. This complexity necessitates the application of systems thinking, which offers a holistic approach. Through analysis of extensive datasets pertaining to various stages of mineral extraction, transportation, processing, and material flows, stakeholders have the ability to identify recurring trends, weaknesses, and potential advantages within the supply chain. The utilization of big data can identify areas with insufficient transparency and potential vulnerabilities in resilience. A comprehensive examination of the mineral supply chain on a global scale provides policymakers with a comprehensive perspective. This enables them to identify any weaknesses, obstacles, and prospective benefits within the system. By considering the bigger picture, policymakers can develop practical solutions that address these issues. Data sharing, systems thinking, and well-informed policies are essential for promoting transparency on a global scale. Data sharing plays a crucial role in creating a cohesive and credible environment for stakeholders to collaborate effectively. By sharing data, stakeholders can gain a unified and comprehensive understanding of the supply chain. This understanding is essential in recognizing the interdependent nature of various components within the supply chain. Consequently, it enables stakeholders to develop more comprehensive and practical solutions.

It is essential not to overlook local challenges while focusing on the bigger picture. It is crucial to address specific issues at the grassroots level, including ESG concerns, in order to ensure a truly sustainable and effective mineral supply chain. As the dynamics of the supply chain are constantly changing, there is an ongoing need for up-to-date insights and strategies. One of the most severe threats of an opaque supply chain is its vulnerability to illegal activities and hidden corruption. The entanglement described here may appear to have a deceptive resilience, making it difficult to dismantle corrupt practices. However, this entanglement is both unsustainable and ethically irresponsible in the long term. This highlights the crucial importance of transparency.

The supply chain resiliency and transparency tool we developed encompasses a range of scales, from the field to the global level. The field-scale analysis tools we developed focus on specific mining sites, investigating the local environmental and social effects, and unpacking the supply chain from the origin of the mineral. This approach ensures the accuracy of our findings and allows us to evaluate the efficacy of potential alternatives that may disrupt the supply chain and facilitate the monitoring of its resiliency and transparency. By employing global-scale analysis, we are able to interpret spatial and temporal patterns within the global supply chain. It is to be noted that the presented approaches require interdisciplinary team and interagency collaborations The global perspective we introduced highlights the movement of minerals in international markets and the potential impact of geopolitical dynamics on the supply chain. The challenges associated with establishing resilient and transparent mineral supply chains can be overcome by an interdisciplinary team of experts and the engagement of local communities, consumers, and investors. Their engagement facilitates a deeper understanding of the challenges and solutions. Furthermore, the engagement of stakeholders increases the likelihood of their support, and contribution towards proposed supply chain changes via the development of effective policies.

References:

[1] International Energy Association, https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions/the-state-of-play

[2] World Bank Report, 2020. Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition.

[3] World Steel Association, https://worldsteel.org/wp-content/uploads/Climate-change-production-of-iron-and-steel-2021.pdf

[4] Demirkan, C., Duzgun, H.S. and Smith, N. A quantitative evaluation of GHG emissions of AHS in Iron Ore Mining Systems (unpublished report).

[5] Aranoglu, F. Flamand, T. and Düzgün, H.S., 2022. Analysis of Artisanal and Small-Scale Gold Mining in Peru under Climate Impacts Using System Dynamics Modeling, Sustainability, Vol. 14, No:12

[6] World Gold Council, https://www.gold.org/

[7] Langeland, A.L.; Hardin, R.D.; Neitzel, R.L. Mercury levels in human hair and farmed fish near artisanal and small-scale gold mining communities in the Madre de Dios River Basin, Peru. Int. J. Environ. Res. Public Health 2017, 14, 302.

[8] UNEP. Annual Report 2012; United Nations Environment Programme: Nairobi, Kenya, 2013.

[9] Duff, P.M.; Downs, T.J. Frontline narratives on sustainable development challenges. Extr. Ind. Soc. 2019, 6, 552–561.

[10] Duzgun, H.S., Smith, N., Flamand, T., Aranoglu, F., Saka, M., Soud, D.,Clough, D.,Seguin K., White. J.,2023. Gold supply chains and corruption. White paper.

[11] Saka, U.M., Duzgun, H.S., Bazilian, M., 2023. Analysis of Trade Data with Machine Learning to Enhance Mineral Supply Chain Transparency Policies. (Manuscript under preparation).