IISE Transactions

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/uiie21

Integrated system dynamics modeling and optimization for artisanal and small-scale gold supply chains

Fatih Aranoglu, Tülay Flamand, Sebnem Duzgun, Gerardo Martinez & Nicole Smith

To cite this article: Fatih Aranoglu, Tülay Flamand, Sebnem Duzgun, Gerardo Martinez & Nicole Smith (15 Mar 2024): Integrated system dynamics modeling and optimization for artisanal and small-scale gold supply chains, IISE Transactions, DOI: 10.1080/24725854.2024.2315166

To link to this article: https://doi.org/10.1080/24725854.2024.2315166 https://doi.org/10.1080/24725854.2024.2315166

Integrated system dynamics modeling and optimization for artisanal and small-scale gold supply chains

Fatih Aranoglu[a], Tülay Flamand[b], Sebnem Duzgun[a], Gerardo Martinez[a], and Nicole Smith[a]

[a]Department of Mining Engineering, Colorado School of Mines, Golden, CO, USA; [b]Business School, University of Colorado Denver, Denver, CO, USA

ABSTRACT

We address artisanal and small-scale gold mining in Peru. Using the data collected through field visits, we develop a System Dynamics (SD) model to examine the current operations of the gold supply chain, and its interplay with mercury and gas suppliers. The current mining operations cause potential health and environmental issues, due to high mercury usage, and other issues (e.g., safety issues). As a potential solution to overcome such problems, we consider incorporating a cyanide processing facility into the SD model, where we examine the amount of ore that a miner would be willing to sell to the facility under several payback scenarios. We formulate a mixed-integer programming model that prescribes the optimal transition plan of a miner from local production to selling their ore to the facility within a time horizon that maximizes a miner's profit. The optimal solution provides a 22% improvement in the miners' profit over that of their current operations. We also conduct a sensitivity analysis to test the sensitivity of the optimal solution to the changes in several input parameters. We discuss that the solution is most sensitive to the gold price changes and the least sensitive to the local production cost changes.

ARTICLE HISTORY
Received 27 March 2023
Accepted 29 January 2024

KEYWORDS
Small-scale gold supply chain; system dynamics modeling; mixed-integer programming

1. Introduction

Artisanal and Small-scale Gold Mining (ASGM) is characterized by its labor-intensive operations with low capital forms of production and processing, and is responsible for the highest amount of mercury emissions globally, since miners often use mercury to process ore-containing gold (UN Environment, 2017). When mercury is added to ore concentrate, it binds to gold particles and forms an amalgam, which is subsequently burned, in order to separate mercury from gold by vaporizing it. Mercury is relatively cheap for miners to purchase, and quick to process so that it allows miners to access cash in a relatively short period of time. However, once mercury is released into the air, inhaling it leads to significant long-term impacts on human health. It also ends up in soils and waterways where they bioaccumulate and pollute ecosystems (Saturday, 2018).

Governments, development organizations, and academia have long grappled with the mercury problem in ASGM. They have taken actions to address mercury use, such as banning mercury altogether, providing artisanal and small-scale miners with mercury capturing equipment (i.e., retorts), and educating miners about the dangers of using mercury (Veiga, Angeloci-Santos, and Meech, 2014). Largely, these efforts have not taken hold for many reasons, such as a lack of sustained training for miners on new technologies (Smith, 2019), inadequate understandings of miners' priorities and motivations (Stocklin-Weinberg *et al.*, 2019), and a mismatch between the type of ore and the introduced technology (Martinez *et al.*, 2021). The mercury problem persists, with mercury emissions from ASGM increasing yearly (Martinez, 2022). Mercury use in gold processing is not prohibited by law; however, the improper use of it that leads to a high amount being released to the environment is one of the main reasons why attempts are being made to reduce its usage. Formal small-scale miners are able to purchase mercury formally with amounts that are associated with their reported production and scale. However, since miners do not follow the most efficient processing guidelines, and since their ore production exceeds the small-scale limit, they end up with mercury shortage, which makes them search for informal ways to buy it, although with higher prices.

In some ASGM regions, cyanide is being added to mineral processing circuits either in tandem with mercury or replacing it altogether (Veiga, Angeloci-Santos, and Meech, 2014). When cyanidation takes place after ore concentrate is treated with mercury, toxic mercury-cyanide complexes can form (Veiga, Angeloci, Hitch, and Velasquez-Lopez, 2014; Drace *et al.*, 2016; Marshall *et al.*, 2020). However, it may be a better alternative to mercury when cyanidation is used alone and adequately. It is more efficient in extracting gold from concentrate, as it can be recycled and decomposed naturally or with oxidizing agents (Sousa *et al.*, 2010; Martinez *et al.*, 2021).

CONTACT Tülay Flamand tulay.flamand@ucdenver.edu
Supplemental data for this article is available online at https://doi.org/10.1080/24725854.2024.2315166

Centralized cyanide processing plants have been installed in some ASGM regions. In most of these cases, government or large- or medium-scale mining companies own and operate the plant and purchase, and process ore from artisanal and small-scale miners. Although central cyanide processing facilities promise to eliminate mercury from mineral processing, there have been relatively few success stories, due to the capital required for installing the facility, the supply of cyanide, and the complexity of the process. Furthermore, Verbrugge *et al.* (2021) suggest that technological changes, particularly central cyanide processing plants, can have significant social impacts by creating and reinforcing inequalities in gold supply chains, with some people who stand to benefit and others who lose. Given these challenges, one model is for artisanal and small-scale gold miners or ASGM communities to own and operate a central processing facility. Not only could this eliminate mercury from ore processing, but it could also recycle water and cyanide for reuse, provide a safer tailings storage facility, and eliminate costs and risks to miners of transporting ore or gold far distances. Ultimately centralized cyanide processing facilities could contribute to more responsible mining practices and better gold traceability.

The mining district of Ananea in the department of Puno is one of the most important mining districts in Peru (Martinez *et al.*, 2021), with 44 formal small-scale mining concessions that produce and process significant amounts of gold using similar methods. Most of these operations use mercury in ore processing, which is vaporized to produce the final product (i.e., dore), and ends up in tailings ponds after ore processing. Tailings storage facilities in this region are often constructed without geotechnical considerations, and have resulted in devastating tailings dam failures in this region. Miners also use water in ore processing that comes from snow melted from nearby glaciers and is pumped to the mine site. Most of the water is not reused in ore processing. Additionally, miners are exposed to criminal threats when transporting the dore from the mine site to the gold buyer.

Ananea presents a viable locale for a central cyanide processing facility. Given the scale of production and the profits yielded by these operations, it is possible that small-scale miners or the community could have the necessary capital to construct and operate a central cyanide processing facility. Since such a facility may address many issues discussed, it is important to show its feasibility and profitability for miners in order to help them in adopting this critical transition from local production to the central processing facility. Therefore, in this article, we model the small-scale gold mining system in Ananea using System Dynamics (SD) modeling, and introduce a cyanide processing plant that buys the Run of Mine (ROM) (i.e., the ore that contains economic gold concentration to be further processed to extract the pure gold from it) from the miners. This offers an understanding of the system's behavior under this technological change. We recognize that technological changes take time to both implement and catch on among their users. Given this, we use the outputs of the SD model to develop a mixed-integer programming model that provides an optimal transition plan from processing the ROM locally on the mine site to sell it to the facility in a way that maximizes the total profit of miners. We demonstrate that a centralized cyanide processing plant in Ananea could increase the gold recovery from ASGM in this region, decrease mercury use and release to the environment, provide a mechanism to reuse water, provide a safer tailings storage facility, and eliminate the safety threats for miners, as they do not need to carry the produced dore to buyers.

The ASGM that we examine in Ananea is a highly complex system due to the intertwined relationships of several supply chain components. In order to capture this complexity, the integrated use of the fieldwork, anthropological research, SD modeling and optimization is crucial. Specifically, fieldwork and anthropological research are conducted to collect data and obtain insights regarding the gold supply chain, however, the information obtained from the fieldwork and anthropological research alone are not sufficient to provide the insights that we need, but they become meaningful with the help of the SD modeling. In particular, using the data collected during the fieldwork and anthropological research, the SD modeling examines how the system changes dynamically over time.

Although SD modeling is a powerful tool that provides these meaningful insights regarding the gold supply chain, it is not able to prescribe optimal decisions that require the development of an optimization model. Particularly, outputs of the SD model are given to the optimization model in order to prescribe the optimal transition plan of a miner based on the system's behavior. This methodology can be applied not only to the gold supply chain examined in this article but also to any supply chain having complex relationships with other supply chains, or among their components. In this case, using the collected data in an SD model provides insights regarding the dynamics of the system by utilizing feedback loops, where the outputs of the system affects the system itself in a recursive way. Then, the insights obtained from the SD model can be embedded into an optimization model to make optimal decisions associated with the supply chain examined. For example, in order to prescribe optimal decisions regarding vaccine types and their associated amount to be supplied for a specific region, first, anthropologists and scientists may visit the area, collect qualitative data and examine the interaction among people and the ways that a particular virus is spreading. Topographical statistics may also be conducted to obtain quantitative data. Using the collected qualitative and quantitative data, an SD model can be developed in order to understand the reaction of the community within the region to different types and amount of vaccine supplies. This reaction can be considered in an optimization model in order to make optimal decisions regarding the type, amount, and price of vaccines in the studied region.

The remainder of this article is organized as follows. Section 2 provides a literature review. Section 3 discusses the proposed methodology. Section 4 includes computational experiments and numerical results. Finally, Section 5 concludes the article with a summary of our work and suggestions for future research.

2. Literature review

Gold supply chains have been increasingly studied in recent years. Fritz *et al.* (2016) examine the interaction between an artisanal and small-scale gold supply chain and the mercury supply chain, and how miners and stakeholders can reduce the consumption of harmful mercury. Thomas *et al.* (2019) conduct interviews with miners and gold buyers to determine the main reasons why they do not sell the produced gold to government-authorized buyer. van der Valk *et al.* (2020) provide a detailed sketch of the gold supply chain in Peru. They divide it into four main stages, namely, the equipment and chemical supply, production, wholesale trade, and retail sales. In the same study, the differences between legal, illegal, and informal activities among the supply chain are well defined.

Some studies examine environmental and security risks that are associated with ASGM. Saturday (2018) discusses the impact on human health and the ecosystem of releasing mercury into the environment. It has been proved that the mercury release from ASGM is increasing annually (UN Environment, 2017). Martinez *et al.* (2021) highlights the effect of using mercury inefficiently in formal small-scale mining and how this reflects on the mercury release and its associated impacts on the environment and human health. Martinez (2022) highlights several examples where miners are attacked by thieves when they are carrying the dore to sell it to gold buyers. Additionally, the author qualitatively discusses the idea of the central processing plant and its similar applications in some regions in Peru.

SD modeling is a new approach to studying and examining minerals and metals supply chains. Sverdrup and Ragnarsdottir (2016) use SD modeling to examine supply and demand of platinum group metals globally over the last 500 years. They examine the delay between the peaks of supply and demand, occurring due to the time required to start a new mining operation and the recycling process of the metal itself. Additionally, SD modeling is used in several studies in the literature such as sustainable supply chain management, transportation, manufacturing, supply chain management (SCM), logistics, life cycle sustainability assessment, and renewable energy supply chains (see Rebs *et al.* (2019) and references therein). Aranoglu *et al.* (2022) is the first study that examines an informal gold supply chain in Peru using SD modeling. They conduct a case study using a flood scenario for the validation process, and examine the effect of external factors such as mercury and fuel shortages on the whole system components. Following Aranoglu *et al.* (2022), this article does not only examine a gold supply chain using the SD modeling, but also utilizes its findings in an optimization model in order to prescribe the optimal transition plan for miners from local production to a central processing facility.

Operations research is used effectively, but not widely, for metal supply chains. Zohal and Soleimani (2016) provide an integrated forward and reverse logistics network of a closed gold supply chain. It contains seven layers, four of which are forward and three of which are reverse so that it simulates the supply and recycling paths. The authors develop a multi-objective integer linear optimization model in order to minimize costs and emissions. Chowdhury *et al.* (2019) develop a new optimization framework for the sustainable design and management of integrated additive manufacturing supply chain networks. Sherwin *et al.* (2020) use fault tree optimization to identify and mitigate the risks among supply chains. Nguyen *et al.* (2020) consider scheduling of multi-echelon assembly supply chain networks that could be applied to the recovery from large-scale disruptive events. Yang *et al.* (2022) develop an optimization model to improve an emergency diesel fuel supply chain during hurricane disaster relief to provide the required energy. Geismar *et al.* (2022) use optimization modeling to achieve optimal design and operation of a second-generation biofuels supply chain. To the best of our knowledge, this article is the first study that develops an optimization model that examines ASGM under a consideration of a central processing facility.

Although the aforementioned studies use SD modeling or optimization models, to the best of our knowledge, there are a limited number of studies that jointly consider them in several application areas. Keloharju and Wolstenholme (1989) provide a case study for policy analyses and design in SD modeling. Duggan (2008) use SD and multi-objective optimization models for policy analysis of complex systems. Chan and Schruben (2008) present an application of optimization in SD, and use optimization models for discrete-event SDs. Xu and Li (2011) use SD modeling for simulating and optimizing a system for use in the coal industry under a fuzzy environment. Liu *et al.* (2013) combine SD and hybrid particle swarm optimization to provide an optimal land use allocation for large areas. Dangerfield and Roberts (2018) provide an overview of strategies and tactics in SD optimization. On the other hand, Li *et al.* (2019) present an SD approach to simulate and optimize water supply and demand balance in Shenzhen in China. In the same context, Li *et al.* (2018) provide a joint SD and optimization approach for supporting sustainable water resources planning in Zhengzhou City in China. Optimization of SD is also implemented in the energy sector. Wu and Xu (2013) use SD for predicting and optimizing energy consumption in world heritage areas. They optimize the carbon emissions using the SD approach. Similarly, He *et al.* (2018) implement the SD approach to simulate the optimization of Chinese power grid investment based on a transmission and distribution tariff policy.

Our extensive literature review shows that there is no study that jointly uses SD modeling and optimization models to prescribe optimal decisions in the metals supply chains (e.g., gold and mercury supply chains that strongly interact). This article makes the following contributions: to the best of our knowledge, this is the first study that examines the formal small-scale gold supply chain in Puno, Peru, jointly using SD modeling and a mixed-integer linear programming model to obtain an optimal transition plan for miners from local production to a central processing facility over a time horizon. The prescribed plan potentially addresses environmental, health, and safety issues that occur due to current production activities of miners within the formal supply chain. The proposed methodology is as follows:

1. We collect data from small-scale surface mines in Ananea through field visits to Peru, and construct the SD model that examine the interaction between gas, mercury and gold supply chains, based on our observations and calculations.
2. We analyze the constructed system and validate our model using the actual data obtained from the field as well as the actual reports from miners.
3. We run the SD model after introducing an alternative flow (i.e., central processing plant) that ensures more profit to miners and eliminates environmental, health, and safety issues.
4. The outputs of the SD model prompt the development of a mixed-integer programming model in order to prescribe an optimal transition plan for the miners from local production to the central processing plan to maximize their profit.
5. We conduct a sensitivity analysis to test the sensitivity of the optimal solution to the changes in model parameters such as production cost, gold price, average local recovery, and cost of mining and transporting to the facility.

3. Proposed methodology

In this section, we provide details of the overall proposed approach. The flow of this approach is shown in Figure 1. The proposed approach starts with the data collection stage including literature review and field work. Specifically, we obtain information from the literature regarding how mining operations such as sluice, amalgamation, and retort actually work. During the field work in Ananea, we visit formal small-scale gold mines to observe and learn about these operations. Specifically, we collect two types of data from the field work. The first type of data, that we will henceforth call “Collected Data”, includes our observations and calculations based on them such as the structure of a mine’s system, the number of each type of machinery used and their capacities. We use the Collected Data to develop the SD and optimization models. The second type of data, that we will henceforth call “Obtained Data”, was directly obtained from a mine and it includes formal information regarding its operations, namely its ore production, gold production and mercury usage amounts. This data is used in the validation process as detailed in the Supplemental Online Materials. After the data collection stage, by using the Collected Data, we develop an SD model in order to understand the system’s response to temporal changes (e.g., change in mercury or gas supply) and their associated effects that occur in the system. At the validation stage, the SD model is validated by comparing its outputs, calculated based on the Collected Data, with the Obtained Data. After validating the model, we integrate an added consideration of a central cyanide processing plant to the SD model and rerun it in order to assess the willingness of a miner to sell their ROM to a

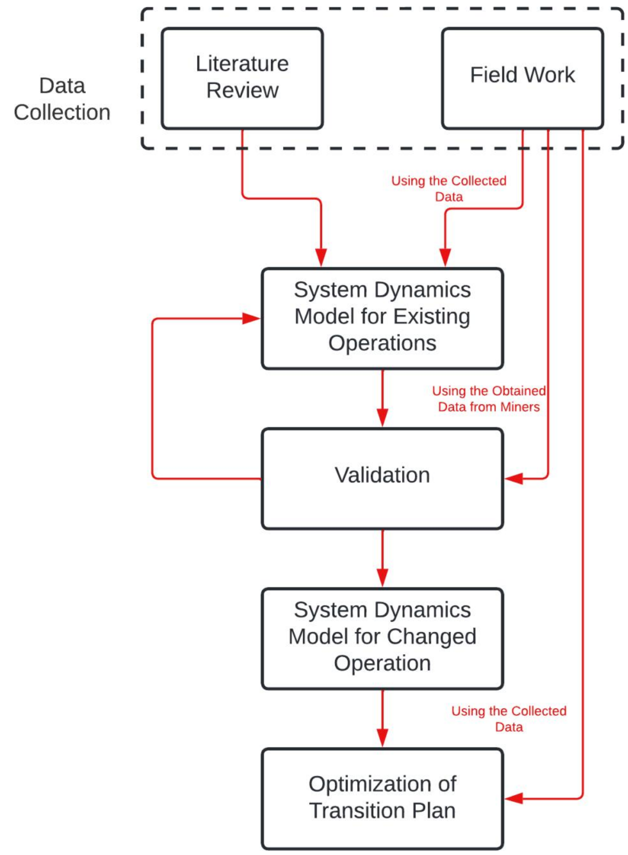

Figure 1. The proposed methodology.

cyanide processing facility in return for several scenarios of specific percentage values of the amount of gold in the ROM paid by the facility. This assessment, along with the use of the Collected Data, prompts the development of a mixed-integer programming model that prescribes an optimal transition plan for a miner over a time horizon to maximize their total annual profit. In addition, we conduct a sensitivity analysis in order to test the sensitivity of the optimal solution to the changes in model parameters (e.g., production cost, gold price, average recovery, and mining and transporting to the facility cost). Each stage of the proposed methodology is detailed in the following subsections.

3.1. Field work

Fieldwork includes two steps. The first step is anthropological research and semi-structured interviews conducted by anthropologists. Specifically, in this step, we collect both qualitative data including the structure of the system and quantitative data including the number of each type of machines, their capacities and other production parameters (i.e., Collected Data) to inform and build the SD model. One of the authors has been conducting research in Puno for over 4 years and has spent a total of 12 months at small-scale mining operations in Ananea. During this time, we qualitatively observe the structure of small-scale mining systems, how information and materials flow, and the relationships and connections between different components of a supply chain. In addition, a mine provided their data sets including information regarding their gold and ore production and mercury usage amounts, to the anthropologists during the semi-structured interviews (i.e., Obtained Data). These data sets are later used for the validation process. Note that the anthropologist, who spent 12 months in the mining area, observed and was told by the mine during the interviews that all mines in the region operate identically. The second step is mining engineers' system observations and data collection from the field work. In this step, the authors also spent a week in Ananea observing and taking measurements on the mining methods. During this week, the team visited five different mining concessions, each of which has several surface mines with similar production systems. We observe that most formal small-scale surface mines in Ananea use the same excavating and hauling equipment. This also indicates that the mining systems of all the mines in the region operate identically, as the anthropologist was told. At the mines, we collect data for the loading cycle of excavators, the traveling cycle of each haulage truck, and the number of haulage trucks per operating excavator. We obtain information from mine operators about the number of shifts per day, the working hours per shift, and the number of working days per year. We also acquire specific types and models of the equipment and use that information to obtain their capacities from the manufacturers' sources. We collect samples of ore from the actual operating locations to measure the grade and density of the ROM. This data also constitutes the part of the Collected Data.

We use the Collected Data to build the SD model and run the stock and flow time-based simulation using the Stella Software. SD modeling provides an advantage of directly applying the qualitative part of the Collected Data to the model, and using them jointly with the its quantitative part. Qualitative data includes the system's structure, information flow, nonnumerical inputs that are used to build the SD model, and the conceptual relations and connections between the SD model nodes (i.e., supply chain components). Once the overall representation of the supply chain is modeled with the qualitative part of the Collected Data, its quantitative part that are calculated by the engineers are also given to the SD model to run the stock and flow time-based simulation.

3.2. SD modeling of formal small-scale surface mining

In this section, we provide details regarding the proposed SD models.

3.2.1. SD model for the current operations

The SD model is constructed based on the Collected Data obtained during the site visit to Ananea, Peru. We observe that the majority of the mines in this region operate identically in terms of their mining method and equipment utilization. Miners operate one excavator that loads five haulage trucks. These trucks transfer ROM to the sluice, where the concentrate is produced. The concentrate is then mixed with mercury to produce the amalgam, a mixture of gold and mercury. The amalgam is burned so that mercury evaporates, leaving a mix of gold and meager amount of mercury which is called dore. Figure 2 shows the complete SD model for the current mining operations of a mine in Ananea. Note that some miners operate their mines with two excavators and 10 hauling trucks; therefore, their ore production, gold production, and mercury use are doubled. The SD model is executed over a time horizon of 288 days, which represent the number of work days per year. There are two shifts per day. We assume that there are four time steps (two for each shift) in each day. The proposed SD model is a discrete model, where the system state changes at some time during each shift. Specifically, some of the ROM flow (highlighted in blue in Figure 2) comes from the "Stock Pile" and some of it comes from the "Initial Tailings Pond" to the "Gravity Separation (Sluice)". Therefore, in each shift, one time step represents the ROM flow from Stock Pile to Gravity Separation, and the other represents the change in the system state where the ROM flows from Initial Tailings Pond to Gravity Separation. In order to take into account the mass balance of this circulating ROM flows, we consider two time steps in each shift.

As shown in Figure 2, the system's operation begins from the ore source (i.e., the mine), and flows to the stockpile via a haulage system. The haulage system contains the excavator, haulage trucks, and variables such as the excavator's capacity, the number of excavators on the mine site, the number and capacity of the haulage trucks required, the fuel availability, and the fuel consumption per machine. All of these variables and parameters have a significant role in determining the mine's production capacity. After that, the ore flows from the stockpile to the physical processing stock. The ore is introduced to a sluice, which is a gravity separation apparatus that is lined with a carpet. When flooded with water and ore, the carpet captures the gold pairing materials (i.e., concentrate). The residual flow from the sluice is transported by front-end loaders to be run through the sluice again to ensure maximum gold recovery. This process is controlled by several variables such as the pumps that are providing water to the sluice, the sluice processing capacity, the fuel availability for the water pumps, the front-end loaders that transport the residual flow from the sluice back to the entrance of the sluice for reprocessing, and the fuel consumption and capacity of the front-end loaders. The concentrate captured by the carpet is bagged and taken to the amalgamation station, where it is mixed with mercury to form an amalgam. The amalgamation process is controlled by the availability of mercury. The by-products from this process are finally deposited into a tailings pond. Once miners have an amalgam, they burn it to vaporize the mercury in order to capture gold. Several operations heat the amalgam in retorts, which capture and reconcentrate the mercury vapors; however, mercury still ends up in the tailings ponds, as we observe that some of the retorts are not working or used properly. The result of this metallurgical process is called dore, which typically contains 90-95% of gold. The miners transport the dore to a larger urban center and sell it to gold buyers, generally on a monthly basis. Although these buyers often offer a reduced price (85% of the global gold price), miners have a few choices regarding to whom to sell their gold.

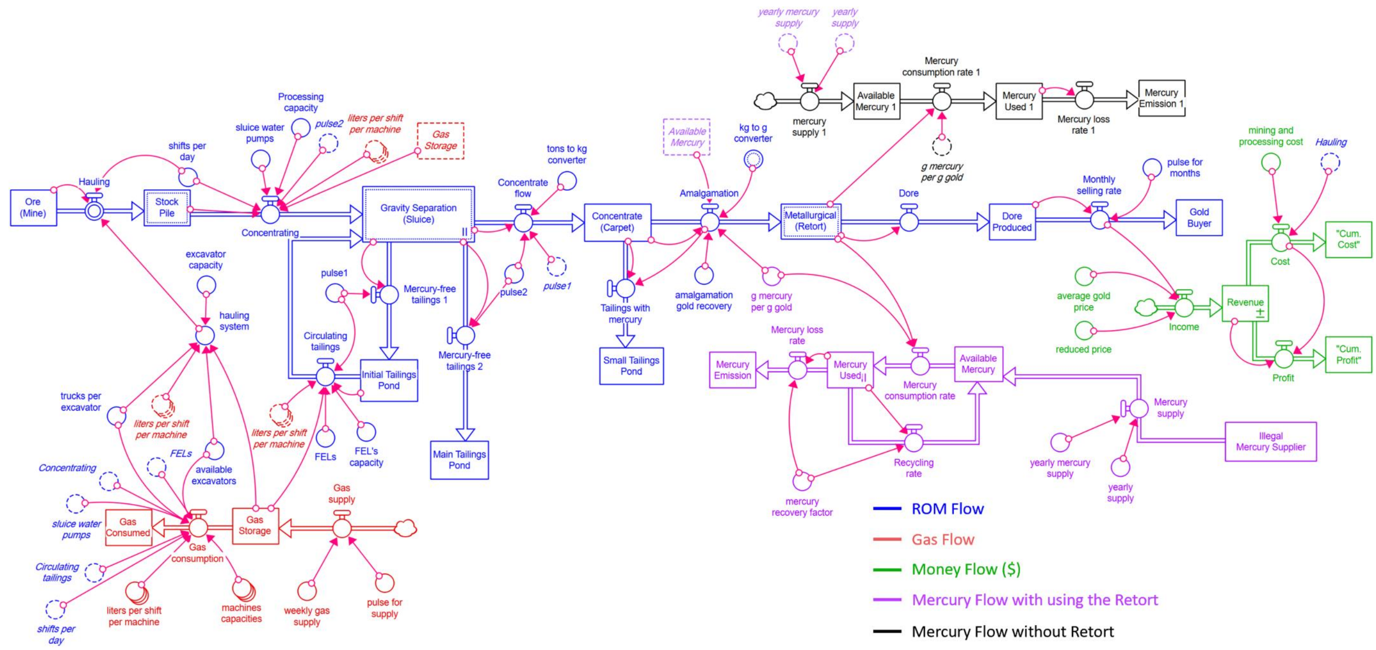

Figure 2. SD model for the current operations: Five main flows are color-coded, each represented by a different color. The boxes represent stocks, the double-line arrows represent flows, and the single-line arrows represent parameters and variables.

The estimated unit cost for mining and processing the ore on the mine site is \$0.3 per ton. In Figure 2, the green flow represents the cash flow that calculates miners' revenue, cost, and profit. The red flow represents the fuel flow, which is controlled by the weekly supply available to the miners, the fuel requirements and fuel consumption rates of the machinery, and the total operating hours. This flow affects the main flow (shown in blue) and also gets affected by it, which is a feedback loop effect. The variables represented by a dashed square or a dashed circle are "ghost" variables that belong to a specific flow and mainly exist in it, but also affect other flows by getting included in those flows as a ghost. For example, gas storage stock belongs to the fuel flow, but it also affects the concentration stage. Therefore, it is represented by a solid box in the gas storage flow (highlighted in orange), and is represented by a dashed box as a ghost and included to the ROM flow (highlighted in blue). The purple flow shows the mercury flow using the retort to recycle the mercury that evaporated from burning the amalgam. The mercury source is generally informal, and the mercury usage is determined by the mercury required to produce one gram of gold and the mercury recovery factor. The black flow in Figure 2 calculates the amount of mercury released to the environment if the retort is used improperly or not at all. It also estimates how many days miners could experience a mercury shortage if they do not use the retort to capture and recycle the mercury, and if mercury is not readily available. See the Supplemental Online Materials for the validation of the SD Model of the current operations.

3.2.2. Introducing a cyanide processing facility to the SD model

After the validation of the SD model for the existing operations, we propose the modified SD model by integrating the consideration of a central cyanide processing facility into the existing SD model. Figure 3 shows the SD model component of this additional consideration.

The updated model calculates the likelihood of a miner selling their ROM to a cyanide processing facility in return for a payment in terms of monetary value, determined by a specific percentage of the amount of gold in the ROM. We will henceforth refer to this specific percentage as "payback percentage". As given by Olyaei *et al.* (2019), we consider that the processing facility can recover up to 95% of the gold in ROM. The updated model is run 10 times for 10 different payback percentages within a range of [25%–34%]. The minimum and maximum values of this range are determined such that they are around 30%, since miners can only recover 30% of the gold in ROM during their local production when using mercury (Martinez, 2022). We use the payback percentage as the main factor for the willingness of a miner to sell their ROM to the facility since our field interviews show that miners would be interested in transitioning to cyanide gold processing in order to contribute to responsible mining. However, simultaneously, they want to keep or increase their profit as it is the main factor for their operations. Due to this reason, and since there is no study that provides the profitability for miners when transitioning to the cyanidation processing, we run the SD model under several payback percentage scenarios. We then record the outputs of each run to be considered in the optimization model. Recall that each model runs with a 288-days time horizon including four time steps per day. Note that the updated SD model includes both the original operations shown in Figure 2 and the integration of the cyanidation processing facility as shown in Figure 3. Specifically, the dashed circle (highlighted in blue) in Figure 3 represents where it connects to the original SD model in Figure 2. In each run, the first part of the model (i.e., Figure 2) is run

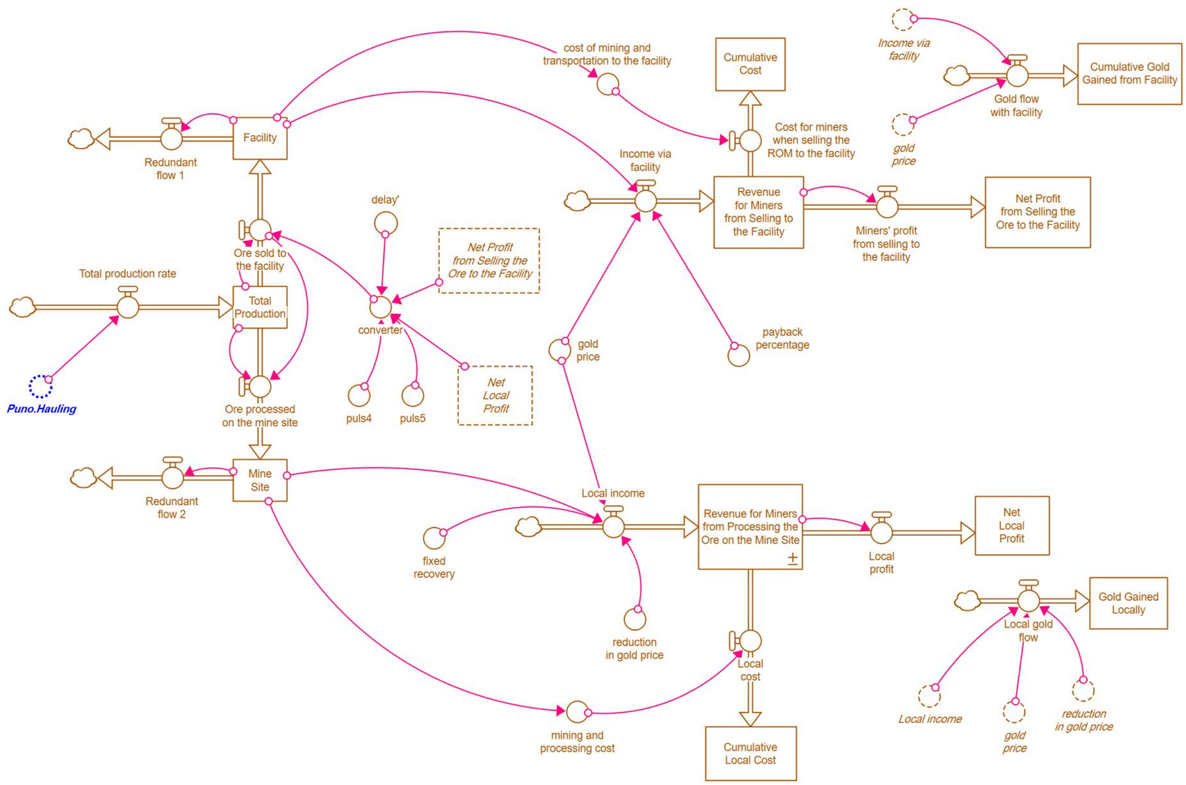

Figure 3. SD Model with consideration of the cyanide processing facility.

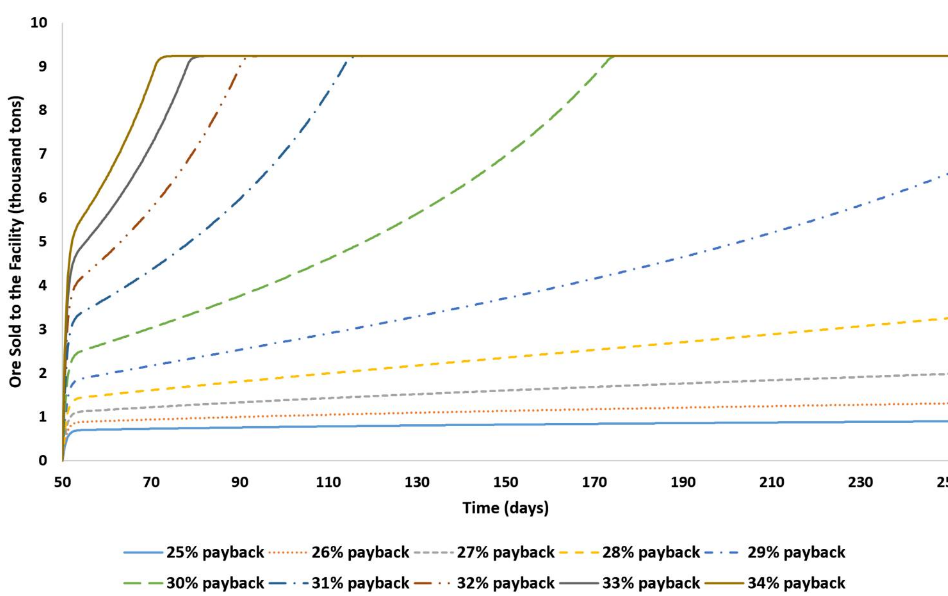

Figure 4. The transition of the miner from local production to selling the ROM to the facility per payback percentage offered.

for 50 days before its second part (i.e., Figure 3) is activated. After 50 days of running the first part, both parts of the model are run together. This ensures that the original operations reach a steady state before the potential change represented by the cyanide processing facility is introduced to the system. Figure 4 compares 10 runs, showing the initial amount of ROM that the miner would be willing to sell to the facility, and the rate of increase in the amount of ROM sold to the facility over time for each payback percentage. Note that the remaining gold that is recovered from the ROM by the processing facility belongs to the facility. In order to ensure precise payments for the accurate gold content in the ROM that is being sold, third-party sampling and testing may be involved in order to test the gold grade of the ROM that is sold to the processing facility.

Once the initial amount of ROM and the increase in this amount that miners sell to the facility over time (until it reaches the maximum ore production) for each percentage payback value is obtained as shown in Figure 4, for each function (color-coded), we fit a linear approximation. Figure 5 illustrates it for only one payback percentage which is 31% from day 50 to day 200. By fitting a linear function,

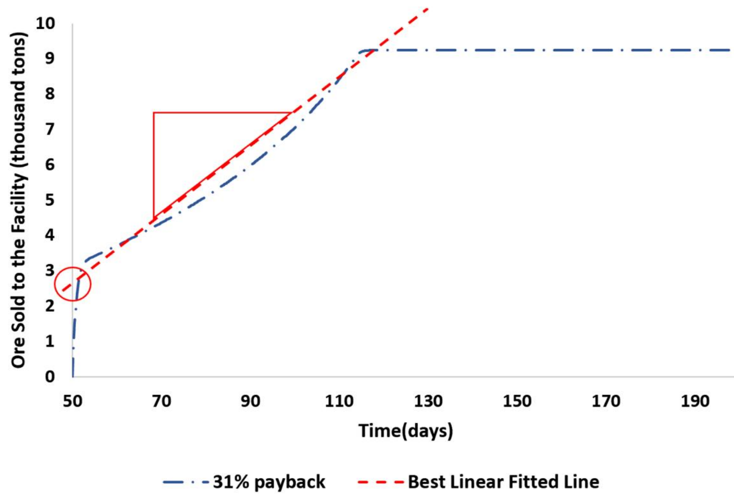

Figure 5. An example of how the increments and initial basis are obtained from the SD Model outputs.

we obtain its intercept (i.e., initial amount of ROM that miners are willing to sell to the facility), and slope (i.e., rate of daily increase in the amount of ROM that miners sell to the facility). Therefore, for each payback percentage value, we obtain a linear function which is given to the optimization model as input. The optimization model considers a time horizon, where each time period spans a month with 24 working days. Therefore, the intercept and slope values obtained from the SD model are multiplied by 24 before they are given to the optimization model.

3.3. Optimization

The proposed SD model simulates the dynamics of the ASGM in Ananea, Peru. Specifically, this model is run for different payback percentage values, which determine the monetary value to be paid to miners in return for selling their ROM to the facility, depending on the amount of gold in it. We consider different payback percentage values as incentives for miners to be convinced to sell their ROM to the proposed facility. The proposed SD model simulates the amount of ROM that miners would be willing to sell to the facility based on a specific payback percentage offered by the facility. As discussed in Section 3.2.2, for each payback percentage value, the proposed SD model is run and a linear function is fit on the output in order to obtain a function of the change in amount of ROM sold to the facility by miners over time. These functions prompt the development of an optimization model. The proposed optimization model takes these functions as input in order to determine the most profitable transition scenario of miners over a time horizon (i.e., a year). The next two sections provide the problem statement and introduce the optimization model.

3.3.1. Problem statement

In this article, we examine the optimal transition plan of miners from processing the ROM locally on the mine site to selling it to a central processing facility where it is processed using the cyanidation method in a way that maximizes the total profit of a miner. Since this transition ultimately reduces the mercury usage to zero, it also yields positive environmental effects. This transition plan includes monthly increase or decrease in the amount of ROM sold to the facility along with the corresponding payback percentage values over a year (i.e., 12 months). The optimization model also suggests the payback percentages offered by the facility every month maximizes the miner's profit, therefore provides them an incentive to make the optimal transition. If a decrease occurs in the amount of ROM sold to the facility in a month, this results in a penalty (i.e., cost) for the miner, since the miner must compensate the profit that the facility would have gained if the decrease did not occur. This type of penalty may be acceptable among miners in similar configurations and may be agreed based on a contract, since the sustainability and profitability of the facility depend on the commitment of miners in selling their ROM to the facility. This is calculated by multiplying the reduced amount of ROM with the gold price and (1- the payback percentage offered to the miner). Note that, considering a specific payback percentage that the facility offers to the miner, the latter represents the remaining percentage that the facility keeps for itself. If there is no increase or decrease in the ROM amount sold to the facility in a specific month, the miner's profit for this month is calculated based on the most recent payback percentage value offered in the previous month. There is also a monthly ROM production capacity so that the amount of ROM sold to the facility each month cannot exceed that capacity. Note that we develop the optimization model as a multi-period model, where the miner gradually transitions from local processing to the processing facility rather than making this transition decision in one time period. We assume this gradual transition is due to the trust factor to be built between the miner and the processing facility. During the fieldwork and the semi-structured interviews, we observed that although the miners tend to consider such a transition, they hesitate making this strategic decision, since giving the entire control of their operations to a third party (i.e., the processing plant) creates a significant risk for them. An illustration of a feasible solution to this problem is given in Figure 6.

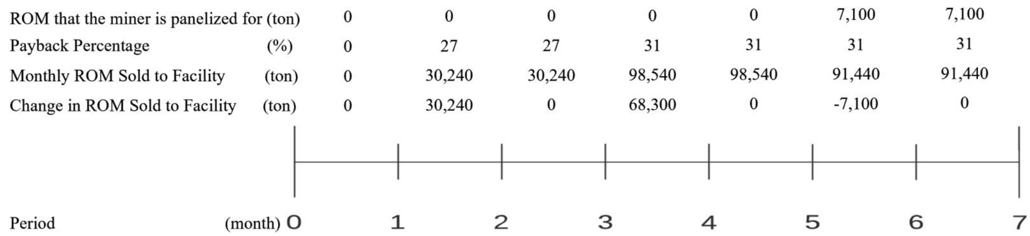

Figure 6. An illustration of a feasible solution.

Table 1. Model Notation.

Sets and Indices		
$i \in \mathcal{P}$	Set of indices that enumerate payback percentages which can be offered by the processing facility	
$t \in \mathcal{T}$	Set of time periods (i.e., months)	
Parameters		*Units*
r_i	The ith payback percentage value	[%]
$\underline{r}$	Minimum of all payback percentage values	[%]
b_i	The initial amount of ROM sold to the facility when the ith payback percentage (r_i) is offered by the facility for the first time	[ton]
d_i	The monthly increase in ROM sold to the facility when the ith payback percentage (r_i) is offered by the facility	[ton]
m	Maximum capacity of the total monthly ROM production	[ton]
p	Average gold price per gram of gold	[$/gram]
s	The reduction percentage in gold price when the miner sells their locally produced ROM directly	[%]
l	The miner's cost of extracting the ROM and locally processing it	[$/ton]
f	The miner's cost of extracting the ROM, selling and transporting it to the facility	[$/ton]
g	Fixed gold recovery percentage of ROM, if it is locally processed	[%]
v	Grade of gold in a ton of ROM	[gram/ton]
Integer Decision Variables		*Units*
Y_t	Increase in the amount of ROM sold to the facility in month t	[ton]
X_t	Decrease in the amount of ROM sold to the facility in month t	[ton]
Continuous Decision Variables		*Units*
F_t	The amount of gold that the miner is paid back by the facility in month t	[gram]
A_{it}	The amount of gold that the facility loses if currently r_i is offered as the payback percentage value, and the miner decreases the amount of ROM sold to it in month t	[gram]
Binary Decision Variables		
R_{it}	1, if and only if the miner selects the ith payback percentage (r_i) offered by the facility in month t, 0 otherwise	
D_t	1, if and only if the miner sells their ROM to the facility for the first time in month t, 0 otherwise	
Z_t	1, if and only if the amount of ROM sold to the facility is increased in month t, 0 otherwise	
B_t	1, if and only if the amount of ROM sold to the facility is decreased in month t, 0 otherwise	
K_t	1, if and only if the amount of gold lost by the facility (due to a decrease made by the miner in the amount of ROM sold to it) in month t is nonzero (i.e., $A_{it} \neq 0$), 0 otherwise	

Figure 6 shows a transition plan of a miner over a time horizon with seven time periods (i.e., months). The plan does not suggest any change in the first month, which implies that the miner processes all the ROM locally on the mine site without selling anything to the facility. In the second month, the plan suggests the miner to sell 30,240 tons of ROM (i.e., increase) to the facility by also suggesting that the facility offers 27% payback to the miner. This means that the facility pays the miner the monetary value of 27% of the gold that 30,240 tons of ROM contains. In the third month, the plan includes no change in the monthly ROM amount sold to the facility. Therefore, the miner sells the same amount with that of the previous period in the third month, which is 30,240. The payback percentage also stays the same which is 27%. The plan implies that the miner increases the amount of ROM that he sells to the facility by 68,300 tons. Since the miner sold 30,240 tons of ROM in the previous month, he sells 98,540 tons of ROM in the fourth month. The plan also suggests that the facility offers the payback percentage of 31% in this case, which is the main incentive for the miner to sell more to the facility. In the fifth month, there is no change in the plan, therefore the miner sells 98,540 tons of ROM again. In the next month, the plan suggest reducing the monthly ROM amount sold to the facility by 7100 tons. Therefore, in the sixth month, the miner sells 91,440 tons to the facility with the same payback percentage with that of the previous period. Note that in this case the miner is penalized for this amount of decrease. Month seven includes no change in the plan, therefore the miner sells 91,440 tons again with the occurrence of the same penalty as in the previous month. Note that Figure 6 is an example of a feasible solution. The optimization model proposed in the next section seeks for the optimal solution that maximizes the total profit of the miner.

3.3.2. Optimization model

In this section, we introduce a Transition Plan Problem (*TPP*) which provides the optimal transition plan of a miner from producing locally to sell their ROM to a central processing facility over a time horizon in a way that maximizes the miner's profit. Consider the notation in Table 1.subject to:

$$TPP : \text{Max} \; \overbrace{\underbrace{\sum_{t\in\mathcal{T}} pF_t}_{\substack{\text{The total revenue}\\ \text{yielded by selling the}\\ \text{ROM to the facility}}} - \underbrace{\sum_{t\in\mathcal{T}} f\Big(\sum_{j=1}^{t} Y_j - \sum_{j=1}^{t} X_j\Big)}_{\substack{\text{The total cost of the miner}\\ \text{for extracting the ROM and}\\ \text{transporting it to the facility}}} - \underbrace{\sum_{i\in\mathcal{P}}\sum_{t\in\mathcal{T}} pA_{it}}_{\substack{\text{The total cost (penalty)}\\ \text{of the miner for reducing}\\ \text{the ROM sold to the facility}}}}^{\text{The net profit of the miner obtained from the ROM sold to the facility}} \tag{1}$$

$$+\overbrace{\underbrace{\sum_{t\in\mathcal{T}} sgpv\Big(m - \sum_{j=1}^{t} Y_j + \sum_{j=1}^{t} X_j\Big)}_{\substack{\text{The total revenue yielded}\\ \text{by locally processing the ROM}\\ \text{and selling the gold directly}}} - \underbrace{\sum_{t\in\mathcal{T}} l\Big(m - \sum_{j=1}^{t} Y_j + \sum_{j=1}^{t} X_j\Big)}_{\substack{\text{The total cost of the miner}\\ \text{for extracting the ROM}\\ \text{and locally processing it}}}}^{\text{The net profit of the miner obtained from the ROM locally processed}} \tag{2}$$

$$Y_t \le b_i D_t + d_i Z_t + m(1 - R_{it}), \quad \forall i \in \mathcal{P}, t \in \mathcal{T} \tag{3}$$

$$Y_t \ge b_i D_t + d_i Z_t - (m + b_i + d_i)(1 - R_{it}), \quad \forall i \in \mathcal{P}, t \in \mathcal{T} \tag{4}$$

$$Y_t \le m Z_t, \quad \forall t \in \mathcal{T} \tag{5}$$

$$\sum_{i\in\mathcal{P}} R_{it} = 1, \quad \forall t \in \mathcal{T} \tag{6}$$

$$R_{i0} = 0, \quad \forall i \in \mathcal{P} \tag{7}$$

$$R_{it} \le R_{it-1} + Z_t, \quad \forall i \in \mathcal{P}, t \in \mathcal{T} \tag{8}$$

$$R_{it} \ge R_{it-1} - Z_t, \quad \forall i \in \mathcal{P}, t \in \mathcal{T} \tag{9}$$

$$2Z_t - \sum_{j=1}^{t} Z_j \le D_t \le Z_t, \quad \forall t \in \mathcal{T} \tag{10}$$

$$\sum_{t\in\mathcal{T}} D_t \le 1, \tag{11}$$

$$B_t \le X_t \le m B_t, \quad \forall t \in \mathcal{T} \tag{12}$$

$$B_t + Z_t \le 1, \quad \forall t \in \mathcal{T} \tag{13}$$

$$0 \le \sum_{j=1}^{t} Y_j - \sum_{j=1}^{t} X_j \le m, \quad \forall t \in \mathcal{T} \tag{14}$$

$$v\underline{r} K_t \le \sum_{i\in\mathcal{P}} A_{it} \le vmK_t, \quad \forall t \in \mathcal{T} \tag{15}$$

$$K_0 = 0, \tag{16}$$

$$A_{i0} = 0, \quad \forall i \in \mathcal{P} \tag{17}$$

$$A_{it} \le vmR_{it}, \quad \forall i \in \mathcal{P}, t \in \mathcal{T} \tag{18}$$

$$A_{it} \le A_{it-1} + X_t v(1 - r_i) + vm(1 - R_{it}) + vm(1 - B_t), \quad \forall i \in \mathcal{P}, t \in \mathcal{T} \tag{19}$$

$$A_{it} \ge A_{it-1} + X_t v(1 - r_i) - vm(1 - R_{it}) - vm(1 - B_t), \quad \forall i \in \mathcal{P}, t \in \mathcal{T} \tag{20}$$

$$A_{it} \le A_{it-1} - Y_t v(1 - r_i) + vm(1 - R_{it}) + vm(2 - Z_t - K_{t-1}), \quad \forall i \in \mathcal{P}, t \in \mathcal{T} \tag{21}$$

$$A_{it} \ge A_{it-1} - Y_t v(1 - r_i) - vm(1 - R_{it}) - vm(2 - Z_t - K_{t-1}), \quad \forall i \in \mathcal{P}, t \in \mathcal{T} \tag{22}$$

$$A_{it} \le A_{it-1} + vm(B_t + Z_t), \quad \forall i \in \mathcal{P}, t \in \mathcal{T} \tag{23}$$

$$A_{it} \ge A_{it-1} - vm(B_t + Z_t), \quad \forall i \in \mathcal{P}, t \in \mathcal{T} \tag{24}$$

$$F_t \le vr_i\left(\sum_{j=1}^{t} Y_j - \sum_{j=1}^{t} X_j\right) + vm(1 - R_{it}), \quad \forall i \in \mathcal{P}, t \in \mathcal{T} \tag{25}$$

$$F_t \ge vr_i\left(\sum_{j=1}^{t} Y_j - \sum_{j=1}^{t} X_j\right) - vm(1 - R_{it}), \quad \forall i \in \mathcal{P}, t \in \mathcal{T} \tag{26}$$

$$A_{it}, F_t \geq 0, \quad \forall i \in \mathcal{P}, t \in \mathcal{T} \tag{27}$$

$$Y_t, X_t \geq 0 \textit{ and integer}, \quad \forall t \in \mathcal{T} \tag{28}$$

$$R_{it}, D_t, Z_t, B_t, K_t \textit{ binary}. \quad \forall i \in \mathcal{P}, t \in \mathcal{T} \tag{29}$$

The objective function (1)-(2) maximizes the total profit of the miner based on the amount of the ROM sold to the facility, as well as that processed locally. Specifically, (1) provides the first by calculating the revenue yielded by selling the ROM to the facility, the total cost of the miner for extracting the ROM and transporting it to the facility, and the total penalty that the miner pays due to the reduction that they made in the amount of ROM sold to the facility. Equation (2) provides the total profit resulted by the locally processed ROM by calculating the revenue of selling the gold obtained from the locally processed ROM directly, and the cost of extracting and locally processing the ROM. Note that $\sum_{j=1}^{t} Y_j + \sum_{j=1}^{t} X_j$ represents the net amount of ROM sold to the facility in month t. In Figure 6, this corresponds to the "Monthly ROM Sold to Facility" row. Y_t is represented by the positive values, and X_t is represented by the negative values in the "Change in ROM Sold to Facility" row. For example, to calculate the amount of ROM sold to the facility in the sixth month (91,440 – the sixth value in "Monthly ROM Sold to Facility" row), all values between the first and the sixth months in the "Change in ROM Sold to Facility" row are summed. Constraints (3)-(4) calculate the increase in the amount of ROM sold to the facility in each month t, depending on the optimal payback percentage offered by the facility. Particularly, if the ith payback percentage is offered in month t, and an increase is made in the amount of ROM sold to the facility, this increase is calculated by $b_i + d_i$ (i.e., the sum of the initial amount and the rate of monthly increase in ROM that the miner is willing to sell to the facility based on the offered payback percentage i), in the case that the miner sells their ROM to the facility for the first time in the given month t. If this is not the first month that the miner is selling the ROM to the facility, then this increase is calculated by d_i only. Constraint (5) ensures that the amount of increase in month t is zero (i.e., $Y_t = 0$), if no increase occurs in that month (i.e., $Z_t = 0$), otherwise this amount is nonzero. Constraint (6) guarantees that in each month t, exactly one payback percentage value must be chosen (i.e., offered by the facility). Constraint (7) initializes the binary variable associated with the selection of payback percentage to zero for month zero. Constraints (8)-(9) ensure that if no increase occurs in the amount of ROM sold to the facility in month t (i.e., either it decreases or does not change), then the payback percentage selected in the previous month is still valid for month t. Constraint (10) identifies the month, when the miner sells their ROM to the facility for the first time, while Constraint (11) ensures that there exists at most one such month. Constraint (12) ensures that the amount of decrease in month t is zero (i.e., $X_t = 0$), if no decrease occurs in that month (i.e., $B_t = 0$), otherwise this amount is nonzero. Constraint (13) ensures that an increase and a decrease in the amount of ROM that is sold to the facility cannot occur simultaneously in each month t. Constraint (14) ensures that the net amount of ROM sold to the facility in month t cannot exceed the monthly ROM production capacity, and must be non-negative. Constraint (15) ensures that the amount of gold lost by the facility due to a decrease made by the miner in month t (i.e., $\sum_{i \in \mathcal{P}} A_{it}$) is nonzero if the binary variable K_t is one, otherwise it is zero. Constraints (16) and (17) initialize variables K_t and A_{it} to zero for month zero. Constraint (18) ensures that the amount of gold that the facility loses is zero for the ith payback percentage (i.e., $A_{it} = 0$), if the ith payback percentage value, r_i is not currently selected (i.e., $R_{it} = 0$), otherwise it takes a nonzero value. Constraints (19)-(20) determine the amount of gold that the facility loses depending on the selected payback percentage value, r_i, if a decrease occurs in month t. Constraints (21)-(22) update this amount depending on the selected payback percentage value, r_i, if an increase occurs in month t, while in previous months, a decrease has occurred. Similarly, Constraints (23)-(24) update this amount depending on the selected payback percentage value, r_i, if neither an increase nor a decrease occurs in month t, while in previous months, a decrease has occurred. Constraints (25)-(26) determine the net amount of gold in grams that the miner is paid back by the facility in month t depending on the selected payback percentage value, r_i. Finally, Constraints (27)-(29) enforce non-negativity and integrality conditions on decision variables.

4. Computational experiments and numerical results

In this section, we provide and discuss our results and findings obtained from the SD and optimization models, as well as the sensitivity analysis, as detailed next.

4.1. Computational results

In this section, we discuss our findings from the SD and optimization models. First, with the SD model, we examine a surface mine, which is a typical mine in Ananea, Peru, with one excavator, five trucks, each with a capacity of 15 m^3, two front end loaders, and two sluices. In the mine, there are three 4-hour shifts per day, and 24 business days in a month. The average specific gravity of the ROM is 2.35.

As discussed in Section 3.2.1, we first run the SD model for the current operations, where the annual production of the mine is 2.42 M tons of ore, and its annual mercury consumption is 38.2 kg. The mine consumes 0.375–0.5 grams of mercury per gram of gold. It has a mining and processing cost of \$0.725 M, and a profit of \$2.810 M per year. We then add a cyanide processing facility into the model, as discussed in Section 3.2.2. We run the model once for each potential payback percentage that the facility may offer to the miner. Our results are reported in Table 2 which shows the initial (base) amount of ROM and its monthly increase that the miner is willing to sell to the facility when the ith payback percentage is offered by the facility. For example, if the facility offers paying the monetary value of 25% of the amount of gold in the ROM sold to it, the miner is initially willing to sell 16,464 tons of ROM, and is willing to increase that amount by 1056 tons every month.

Our results in Table 2 are used in the proposed optimization model as inputs. The optimization model is run using AMPL/Gurobi 9.5.1 with Dell OptiPlex 7090, which has an Intel(R) Core(TM) i7-10700 CPU with eight 2.90GHz cores, 16 gigabytes RAM and 256 gigabytes of SSD.

The proposed optimization model yields the optimal transition plan for the miner from local production to selling their ROM to the processing facility in a way that maximizes the miner's profit. The prescribed optimal transition plan over a year horizon is given in Figure 7.

The optimal objective value (i.e., profit) is $3.428 M, and the optimal solution suggests that the miner sells 90,000 tons of ROM to the facility in the first month, while processing the remaining ROM locally. Doing so, the miner gets paid the monetary value of 30% of the gold in the ROM sold to the facility. Therefore, the facility gets the remaining 70% of the gold for itself. Note that the processing method utilized by the facility can recover up to 95% of the gold in the ROM (Olyaei *et al.*, 2019), while with the local processing, miners can recover at most 30% of the gold in the ROM (ore). For the following month, the optimization model suggests that the miner increases the amount of ROM sold to the facility by 130,000 tons. This results in total of 220,000 tons of the ROM sold to the facility in the given month. By doing so, the miner gets paid the monetary value of 34% of the gold in the ROM. For the remaining months, the miner sells their maximum ROM production to the facility and gets paid for the monetary value of 34% of the gold in the ROM. Note that the optimal objective value ($3.428 M) prescribed by the optimization model based on the optimal transition plan provides a 22% improvement over the profit based on the miner's current operations where all the ROM is processed locally ($2.810 M). Note that the miner's current profit is calculated by providing the actual parameter values to the optimization model and obtaining the objective value. This value can also be calculated using the SD model in the same manner.

Table 2. The initial (base) amount of ROM and its monthly increase that the miner is willing to sell to the facility with each payback percentage is offered by the facility.

r_i (%)	b_i (tons)	d_i (tons)
25	16,464	1056
26	20,760	2040
27	26,400	3840
28	33,600	7104
29	43,680	13,920
30	58,320	32,232
31	78,240	68,328
32	96,480	89,472
33	112,560	112,968
34	126,960	129,264

4.2. Sensitivity analysis

In this section, we conduct a sensitivity analysis in order to test the sensitivity of the optimal solution to the changes in certain paramaters, namely unit local production cost l, fixed local recovery g, gold price p and unit facility production cost f. To this end, we change the value of each parameter by decreasing and increasing its value within the range of [-20%, 20%]. Our results are given in Figure 8.

In Figure 8, each linear function represents the sensitivity associated to a specific parameter. A steeper slope of a function reveals higher sensitivity of the solution to the related parameter. Results show that the solution is the most sensitive to the gold price, and the least sensitive to the local production cost. The sensitivity of the solution to a decrease in the fixed local gold recovery percentage is low, while it becomes more sensitive when there is an increase in this parameter. Particularly, if the fixed local recovery percentage is increased to a point where the local processing is more profitable, and the entire ROM is processed locally, then the solution becomes more sensitive to it. Regarding the unit facility production cost, the more it is decreased, the more ROM the miner sells to the facility, therefore gets more profit. On the other hand, the more it is increased, the more ROM the miner processes locally which is not as profitable.

Note that although Figure 8 reveals that the effects of all these parameters are linear, it is noteworthy that these effects are specific to the gold supply chain in Ananea, since they are heavily data-dependent. Although the optimal solution may look straightforward for this data, trade-offs in this problem are not straightforward to be assessed manually without using an optimization model while making decisions. In fact, we artificially generated several data sets with different structures and observed that, for example, if the local gold recovery percentage of ROM g fluctuates over time, the optimal solution considers a trade-off between the penalty of not selling the ROM to the facility in some months and profit of keeping the ROM to be processed locally to maximize the profit over time. Optimal solutions when the gold price is changed by +20% and -20%, and the unit facility production cost is changed by +20% and -20% are discussed in the Supplemental Online Materials.

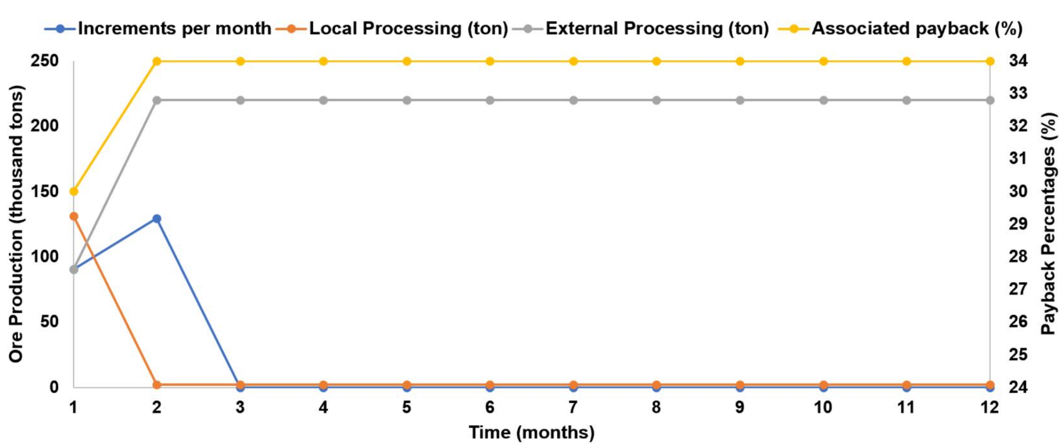

Figure 7. The optimal transition plan of the miner from processing gold locally to selling the ROM to the facility.

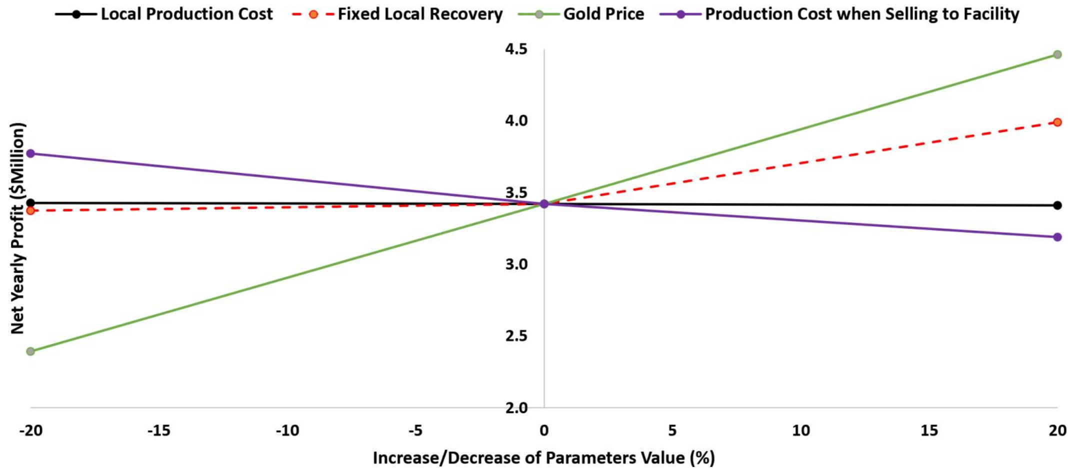

Figure 8. Results of the sensitivity analysis.

5. Conclusion

In this article, we examine artisanal and small-scale gold supply chains in Ananea, Puno, Peru. We first collect data from small-scale mines in Ananea through the field visits, which prompt the development of an SD model for the current operations of a typical mine in this area to understand its dynamics. Since these operations potentially cause environmental, health and safety issues due to several reasons such as high mercury use and being exposed to threats from criminals during the transportation of gold, we consider a cyanide processing facility that would eliminate such issues for the miners. This processing facility does not use any mercury, instead it processes the ROM using cyanide. It buys the ROM from miners, and in return, pays them monetary value of a specific percentage of gold in the ROM. We incorporate the consideration of a processing facility into the SD model to analyze the amount of ROM that the miners would be willing to sell to the facility under 10 different payback percentages that the facility would potentially offer to them. Using this analysis, we then develop an optimization model that prescribes the optimal transition plan of a miner from local production to selling their ROM to the facility in a way that maximizes the miner's profit. The optimal solution provides a 22% improvement in the miner's net profit over the profit resulted in their current operation where all the ROM is processed locally. In addition, we conduct a sensitivity analysis to test the sensitivity of the optimal solution to the changes in several input parameters. Our results show that the optimal transition plan is most sensitive to the changes in gold price and the least sensitive to the changes in local production cost. As for future work, all the mines in Ananea can be considered and an optimization model can be developed for prescribing strategic decisions regarding the processing facility such as its location.

Funding

This material is based upon work supported by the National Science Foundation under Grant No. 1935630. Any opinions, findings, conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

Notes on contributors

Fatih Aranoglu received his BS in Mining Engineering and Geotechnical Engineering both from Middle East Technical University in July 2020 with High Honors, and ranked the first of the Department of Mining Engineering. In August of the same year, he started his PhD studies in Earth Resources Development Engineering program at Colorado School of Mines. He is currently a Research Assistant, and a Teaching Assistant for the Introduction to Systems Engineering course, and Graduate Student Government Representative of the Department of Mining Engineering at Colorado School of Mines. His research area focuses on gold mining applications using System Dynamics and Mathematical Modeling.

Dr. Tulay Flamand is an Assistant Professor in the University of Colorado Denver Business School. Her research focuses on data analytics and optimization, applied to retail analytics, sports analytics, mining operations, small-scale gold supply chains and energy. It also includes developing effective exact and heuristic solution methodologies for solving challenging optimization problems. Her work has been published in journals such as *Operations Research, INFORMS Journal on Computing, European Journal of Operational Research, IISE Transactions, Journal of the Operational Research Society, Omega.*

Dr. H. Sebnem Düzgün is a Professor and Fred Banfield Distinguished Endowed Chair of the Mining Engineering Department at the Colorado School of Mines (CSM). She has also joint faculty appointment in the Department of Computer Science at CSM. Dr. Düzgün has an international reputation for a broad range of topics including big data and AI in the mining life cycle, probabilistic modeling of engineered and natural rock slopes and quantitative risk assessment, analysis and management of risks associated with geotechnical hazards and tailing dam failures, mine environmental monitoring using remote sensing, virtual/augmented/mixed reality and serious gaming for technical training and collaborative decision making. She authored four books and published over 250 papers.

Gerardo Martinez received his PhD from Colorado School of Mines in earth resources development engineering. He received his MS in environmental engineering from the University of California, Davis. His master's thesis focused on mercury contamination in watersheds due to uncontrolled gold mining in the Madre de Dios region of Peru. Gerardo, a 2015 EPA STAR Fellow, has over seven years of laboratory and research experience. He is currently studying the opportunities and challenges associated with formalization of artisanal and small-scale gold mining in the Puno region of Peru. His previous work at Syracuse University focused on the fate and transport of mercury and nutrients in an agricultural constructed wetland.

Nicole M. Smith is an assistant professor in the mining engineering department at the Colorado School of Mines. She is a cultural anthropologist with research and teaching interests in artisanal and small-scale mining, mining and sustainable development, corporate social responsibility, and rural livelihoods.

ORCID

Fatih Aranoglu http://orcid.org/0000-0001-9547-6252

Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article.

References

Aranoglu, F., Flamand, T. and Duzgun, S. (2022) Analysis of artisanal and small-scale gold mining in Peru under climate impacts using system dynamics modeling. *Sustainability*, **14**(12), 7390.

Chan, W.K. and Schruben, L. (2008) Optimization models of discrete-event system dynamics. *Operations Research*, **56**(5), 1218–1237.

Chowdhury, S., Shahvari, O., Marufuzzaman, M., Francis, J. and Bian, L. (2019) Sustainable design of on-demand supply chain network for additive manufacturing. *IISE Transactions*, **51**(7), 744–765.

Dangerfield, B. and Roberts, C. (2018) An overview of strategy and tactics in system dynamics optimization, in M. Kunc (ed.), *System Dynamics: Soft and Hard Operational Research*, Palgrave Macmillan, London, UK, pp. 165–196.

Drace, K., Kiefer, A.M. and Veiga, M.M. (2016) Cyanidation of mercury-contaminated tailings: Potential health effects and environmental justice. *Current Environmental Health Reports*, **3**(4), 443–449.

Duggan, J. (2008) Using system dynamics and multiple objective optimization to support policy analysis for complex systems, in H. Qudrat-Ullah, J. M. Spector, and P. I. Davidsen (eds.), *Complex Decision Making: Theory and Practice*, Springer, Berlin, Heidelberg, pp. 59–81.

Fritz, M.M., Maxson, P.A. and Baumgartner, R.J. (2016) The mercury supply chain, stakeholders and their responsibilities in the quest for mercury-free gold. *Resources Policy*, **50**, 177–192.

Geismar, H.N., McCarl, B.A. and Searcy, S.W. (2022) Optimal design and operation of a second-generation biofuels supply chain. *IISE Transactions*, **54**(4), 390–404.

He, Y., Jiao, J., Chen, R. and Shu, H. (2018) The optimization of Chinese power grid investment based on transmission and distribution tariff policy: A system dynamics approach. *Energy Policy*, **113**, 112–122.

Keloharju, R. and Wolstenholme, E.F. (1989) A case study in system dynamics optimization. *Journal of the Operational Research Society*, **40**(3), 221–230.

Li, T., Yang, S. and Tan, M. (2019) Simulation and optimization of water supply and demand balance in shenzhen: A system dynamics approach. *Journal of Cleaner Production*, **207**, 882–893.

Li, Z., Li, C., Wang, X., Peng, C., Cai, Y. and Huang, W. (2018) A hybrid system dynamics and optimization approach for supporting sustainable water resources planning in Zhengzhou City, China. *Journal of Hydrology*, **556**, 50–60.

Liu, X., Ou, J., Li, X. and Ai, B. (2013) Combining system dynamics and hybrid particle swarm optimization for land use allocation. *Ecological Modelling*, **257**, 11–24.

Marshall, B.G., Veiga, M.M., da Silva, H.A. and Guimarães, J.R.D. (2020) Cyanide contamination of the Puyango-Tumbes river caused by artisanal gold mining in Portovelo-Zaruma, Ecuador. *Current Environmental Health Reports*, **7**(3), 303–310.

Martinez, G. (2022) Formalization, certification, and technology: The complex landscape of artisanal and small-scale gold mining interventions in Peru. Ph. D. thesis, Colorado School of Mines, Golden, CO, USA.

Martinez, G., Smith, N.M. and Malone, A. (2021) Formalization is just the beginning: Analyzing post-formalization successes and challenges in Peru's small-scale gold mining sector. *Resources Policy*, **74**, 102390.

Nguyen, H., Sharkey, T.C., Mitchell, J.E. and Wallace, W.A. (2020) Optimizing the recovery of disrupted single-sourced multi-echelon assembly supply chain networks. *IISE Transactions*, **52**(7), 703–720.

Olyaei, Y., Noparast, M., Tonkaboni, S.Z.S., Haghi, H. and Amini, A. (2019) Response of low-grade gold ore to cyanidation and thiourea leaching. *Particulate Science and Technology*, **37**(1), 86–93.

Rebs, T., Brandenburg, M. and Seuring, S. (2019) System dynamics modeling for sustainable supply chain management: A literature review and systems thinking approach. *Journal of Cleaner Production*, **208**, 1265–1280.

Saturday, A. (2018) Mercury and its associated impacts on environment and human health: A review. *Journal of Environmental Health Science*, **4**, 37–43.

Sherwin, M.D., Medal, H.R., MacKenzie, C.A. and Brown, K.J. (2020) Identifying and mitigating supply chain risks using fault tree optimization. *IISE Transactions*, **52**(2), 236–254.

Smith, N.M. (2019) "Our gold is dirty, but we want to improve": Challenges to addressing mercury use in artisanal and small-scale gold mining in Peru. *Journal of Cleaner Production*, **222**, 646–654.

Sousa, R.N., Veiga, M.M., Klein, B., Telmer, K., Gunson, A.J. and Bernaudat, L. (2010) Strategies for reducing the environmental impact of reprocessing mercury-contaminated tailings in the artisanal and small-scale gold mining sector: Insights from Tapajos River Basin, Brazil. *Journal of Cleaner Production*, **18**(16–17), 1757–1766.

Stocklin-Weinberg, R., Veiga, M.M. and Marshall, B.G. (2019) Training artisanal miners: A proposed framework with performance evaluation indicators. *Science of The Total Environment*, **660**, 1533–1541.

Sverdrup, H.U. and Ragnarsdottir, K.V. (2016) A system dynamics model for platinum group metal supply, market price, depletion of extractable amounts, ore grade, recycling and stocks-in-use. *Resources, Conservation and Recycling*, **114**, 130–152.

Thomas, M.J., Veiga, M.M., Marshall, B.G., Dunbar, W.S. *et al.* (2019) Artisanal gold supply chain: Measures from the Ecuadorian government. *Resources Policy*, **64** (C).

UN Environment. (2017) Global mercury supply, trade and demand. United Nations Environment Programme, Chemicals and Health Branch. Geneva, Switzerland. Available at https://wedocs.unep.org/bitstream/handle/20.500.11822/21725/global_mercury.pdf?sequence=1&isAllowed=y (accessed 3 January 2024).

van der Valk, N., Bisschop, L. and van Swaaningen, R. (2020) When gold speaks, every tongue is silent: The thin line between legal, illegal, and informal in Peru's gold supply chain, in Y. Zabyelina, D. van Uhm (eds.), *Illegal Mining: Organized Crime, Corruption, and Ecocide in a Resource-Scarce World*, Springer, Cham, pp. 299–327.

Veiga, M.M., Angeloci, G., Hitch, M. and Velasquez-Lopez, P.C. (2014) Processing centres in artisanal gold mining. *Journal of Cleaner Production*, **64**, 535–544.

Veiga, M.M., Angeloci-Santos, G. and Meech, J.A. (2014) Review of barriers to reduce mercury use in artisanal gold mining. *The Extractive Industries and Society*, **1**(2), 351–361.

Verbrugge, B., Lanzano, C. and Libassi, M. (2021) The cyanide revolution: Efficiency gains and exclusion in artisanal-and small-scale gold mining. *Geoforum*, **126**, 267–276.

Wu, Z. and Xu, J. (2013) Predicting and optimization of energy consumption using system dynamics-fuzzy multiple objective programming in world heritage areas. *Energy*, **49**, 19–31.

Xu, J. and Li, X. (2011) Using system dynamics for simulation and optimization of one coal industry system under fuzzy environment. *Expert Systems with Applications*, **38**(9), 11552–11559.

Yang, H., Duque, D. and Morton, D.P. (2022) Optimizing diesel fuel supply chain operations to mitigate power outages for hurricane relief. *IISE Transactions*, **54**(10), 936–949.

Zohal, M. and Soleimani, H. (2016) Developing an ant colony approach for green closed-loop supply chain network design: A case study in gold industry. *Journal of Cleaner Production*, **133**, 314–337.