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RESEARCH PAPER

Evaluation of the extractive gold process: open-pit mining through exergy analysis

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Abstract

The Colombian mining sector is characterized by the production of coal, nickel, emeralds, gold, and construction materials. It is considered by the National Development Plan of Colombia 2018−2022 as an economic agent that boosts development in the region and one that requires the strengthening of its policies and environmental liability. Therefore, this paper aims to show the importance of implementing methodologies based on the logic of nature (exergy) that objectively indicate the environmental impact of an extractive gold activity, such as open-pit gold mining. The extractive activity or process to be studied consists of the following stages: topsoil removal by using machinery and explosives to create craters and to access the mineral present in the subsoil; the physical transformation of the extracted material through crushing, grinding, gravimetric separation, flotation, leaching, adsorption, elution, and electrodeposition, along with smelting and casting to obtain gold and silver ingots. Thus, this paper analyzes the exergy performance of each unit process of the open-pit extractive process. The obtained results are used in a sensitivity analysis, which determines the system efficiency, by assuming the increase of gold in the extracted material in the exploitation stage, by using the same supplies and input of the current process. In other cases, the open-pit mining process is analyzed by changing its technologies in the mining process and assuming that this change reduces the inlet ore to 60%, by discarding 40% of material without gold and by reducing supply consumption by 25%. By improving the system efficiency, the exergy destroyed is reduced and the emissions to the environment diminish. Therefore, this method may be implemented as a basic guideline when it comes to decision-making processes in the planning of the extractive processes by integrating the environmental component with gold production.

Keywords: exergy, exergetic cost, extractive gold process, open-pit mining, silver and gold

1. Introduction

Since the industrial revolution, societies have increased their energy demand in an exponential way, rendering the efficient use of energy a fundamental issue, especially due to the economic and environmental problems associated with its misuse [1]. Thus, in order to use energy resources more efficiently in any process, first of all, the different flows and energy transformations involved must be clearly determined. However, according to the First Law of Thermodynamics, energy is rather a conservative magnitude and, as such, it is neither possible to destroy it nor create it, instead it is only possible to transform it from one form into another [2]. On the other hand, the Second Law of Thermodynamics states that although energy cannot be created or destroyed, its quality may be actually degraded [3]. Thus, in order to perform a thorough energy analysis, it is also necessary to bear in mind the statement of the Second Law of Thermodynamics, from which the concept of exergy springs. Exergy is defined as the maximum work that can be obtained when

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a quantity of matter is led to a state of full thermodynamic (thermo-mechanical and chemical) equilibrium with the environment, by involving only reversible interactions with the components thereof in order to produce the same components of the environment [4]. For this reason, exergy is the maximum potential to produce work of a substance or a flow when the environment in which it is contained is defined. It is important to note that exergy, unlike energy, is not subject to the law of conservation, since the irreversibility inherent to the real processes destroys at least part of it. Accordingly, in light of the irreversible nature of the real processes, the exergy concept is more appropriate for evaluating the behavior of energy systems as it combines the law of conservation of energy with the entropy generation concept. Therefore, regardless of the classification of the energy resource, either substance (e.g. fuel, air, water, and minerals) or exergy flow (i.e. heat or power), the performance of the assessment of any energy system, industrial plant, or even an economic activity, can be rationally achieved. In fact, exergy efficiency is a valuable indicator that quantifies the fraction of the total energy consumed by a system that can be potentially transformed into useful work.

Since the first decade of the 21st century, mining and its sustainability have been an ongoing topic for discussion due to the public interest in current environmental degradation. The first attempts to quantify sustainability arose from the use of thermodynamic principles in an ecological field to measure the sustainability of ecological systems [5]. Emergy Analysis was one of the first attempts, followed by other conceptual tools like Exergy Analysis and Life Cycle Assessment [6]. These methods, which have been widely discussed and employed in literature, attempt to assess the sustainability of different production systems in terms of energy, exergy, and/or life cycle analysis from an accounting perspective, but under different points of view. This is because "sustainability" has no clear and distinct meaning due to its multidimensional intrinsic nature [7]. Methods like exergy or emergy, are based on ecological, economic, thermodynamic, ecological-economic, public policy, and planning theory approaches [8]. All these methodologies lead to the same thing: tools that provide decision-makers with indicators of environmental, economic or social sustainability for the formulation and implementation of public policies. These indicators can be taken as individual or composite parameters, i.e. synthetic aggregations of independent parameters reflecting the values of interested parties and the considerations of the experts [9]. Life Cycle Assessment and Exergy Analysis are "User-Side" methods while Emergy Accounting has a "Donor-Side" perspective, which provides a comprehensive and integrated image for environmental decision making. Exergy Analysis represents the minimum amount of energy (work) and raw material used in a single process. Emergy Evaluation focuses on the use of renewable/non-renewable energy, whereas Life Cycle Assessment evaluates the environmental impacts associated with emissions generated by the use of resources[10].

Exergy analysis is a very useful tool when the goal is to measure the efficient use of energy and material resources, and therefore, it also assesses the loss of resources that participate in the process. The exergy associated with polluting emissions can be seen as potentially harmful to the environment. The waste, which is notin thermodynamic equilibrium with the environment, has a high potential of producing unfavorable changes in the environment of the analyzed system[10].

One of the main drawbacks of the dominant environmental assessment and economic model is that it neglects the limitations that physical principles, such as the Second Law of Thermodynamics, impose on productive systems. Two traditional misconceptions exist in most economic development models. Firstly, it has been often assumed that the natural resources available in the biosphere are free. Even worse, in many cases, it has been assumed that those resources are unlimited, which has caused the extraction and use of natural resources at a rate that does not allow their renewal [11, 12]. Mineral resources are considered to be non-renewable because they cannot be manufactured, reused, or regenerated at a rate that can sustain their consumption. In the past, economists did not care about mineral depletion, global warming or energy efficiency.

In Colombia, gold was used by multiple pre-Columbian indigenous cultures and its extraction was carried out in a simple way by taking advantage of the density difference and its fusion at high temperatures. This is considered to be a clean process when compared with current methods, which consist of two most commonly used extraction methods: mercury amalgamation and cyanidation [13]. In summary, the mining process consists of the exploitation or extraction of the minerals which were accumulated in the soil or subsoil in the form of deposits and whose activity is described in four stages: exploration, exploitation, benefit, and smelting. The difference between each mining process lies in its size and the applied technologies for each step, but the aforementioned stages are maintained. At present, the following basic types of mining are recognized: surface or open-pit mining, underground mining, well drilling, underwater mining or dredging [14, 15]. Therefore, the objective of this research is to evaluate open-pit gold mining activity by means of exergy analysis and exergy efficiency, from its exploration stage to the smelting stage, by involving all the unit processes that this entails.

1.1. Open-pit gold mining activity

Fig. 1, Tables 1–5 shows anopen-pit mining process flow diagram of the study case, which is divided into five stages, ranging from the mining stage to the smelting stage, and which comprises the inherent process of the mining activity, showing the input of matter and energy for every single process [16]. It is important to highlight that the principal yellow flows indicate the gold content within the flows, in order to differentiate them from the material without any gold content. This means that for every input flow to every process, a mass of gold in proportion to the input flow exists. For example, in the input of the grinding process, a current of rocks with a content of gold of 0.00006% existsand the remaining 99.999994% needed to reach 100% corresponds to material without any gold content. This is important because it shows that the amount of gold is little compared with the resulting the rocks and graves along the mining activity.

The mining or exploitation stage, being the first stage, comprised the processes related to the appropriateness of land areas, mineral extraction and preparation for grinding. This stage also includesthe stripping of topsoil.

The second stage or beneficiation stage comprised the processes which boost the gold separation process, based on its physical properties.

The third stage or refining stage comprised of the processes which boost the gold separation process, based on its chemical properties.

The fourth stage or the smelting stage is the stage at which silver and gold are obtained.

The fifth stage or the waste treatment stage is the one in which the final disposition of waste coming from each process, either for recirculation or storage, takes place.

The previous tables describe the stage-by-stage mining, showing the input and output of matter and energy for each process. Thus, achieving detail for the exergy analysis, which is calculated with the help of the Engineering Equation Solver (EES) software.

2. Methodology

The methodology used is based on the one proposed by Valero [12]. In her doctoral thesis, she proposes a methodology which is capable of evaluating the natural capital of the earth from its minerals, as a non-reactive mixture or with a coefficient of reactivity equal to one, where the natural capital of the earth is calculated like the chemical exergy of a solution, combined with a traditional exergy analysis.

2.1. Exergy and natural resources assessment

A fundamental law of nature, the First Law of Thermodynamics, tells us that energy and matter can be neither created nor destroyed. The Second Law places additional limits on energy transformations and reflects qualitative characteristics. It states that energy can be transformed, but its quality is diminished. Locally, the quality can be improved, but this can only occur at the expense of greater deterioration of quality elsewhere. The level of quality deterioration or disorder is measured through the entropy property [17].

Exergy is defined as the maximum work that can be achieved when a quantity of matter is carried to a state of thermodynamic equilibrium with the environment, by involving interactions with components of the environment through reversible processes only [4]. It is important to note that exergy, unlike energy, is not subject to the Law of Conservation: the irreversibility that can arise in the process destroys at least part of the exergy. The exergy concept may be more appropriate for evaluating the behavior of energy systems because it combines the Law of Conservation of Energy with the entropy generation concept. In conclusion, “The combination of both laws indicates that it is not a question of the existent amount of mass or energy, but on the quality of that mass or energy, or in other words on its exergy content” [12]. “Exergy analysis is a powerful tool for improving the efficiency of processes and systems. This leads to less resources to be used and the emission of less wastes to the environment. However, it is a much more useful concept, and can be applied for resource accounting.

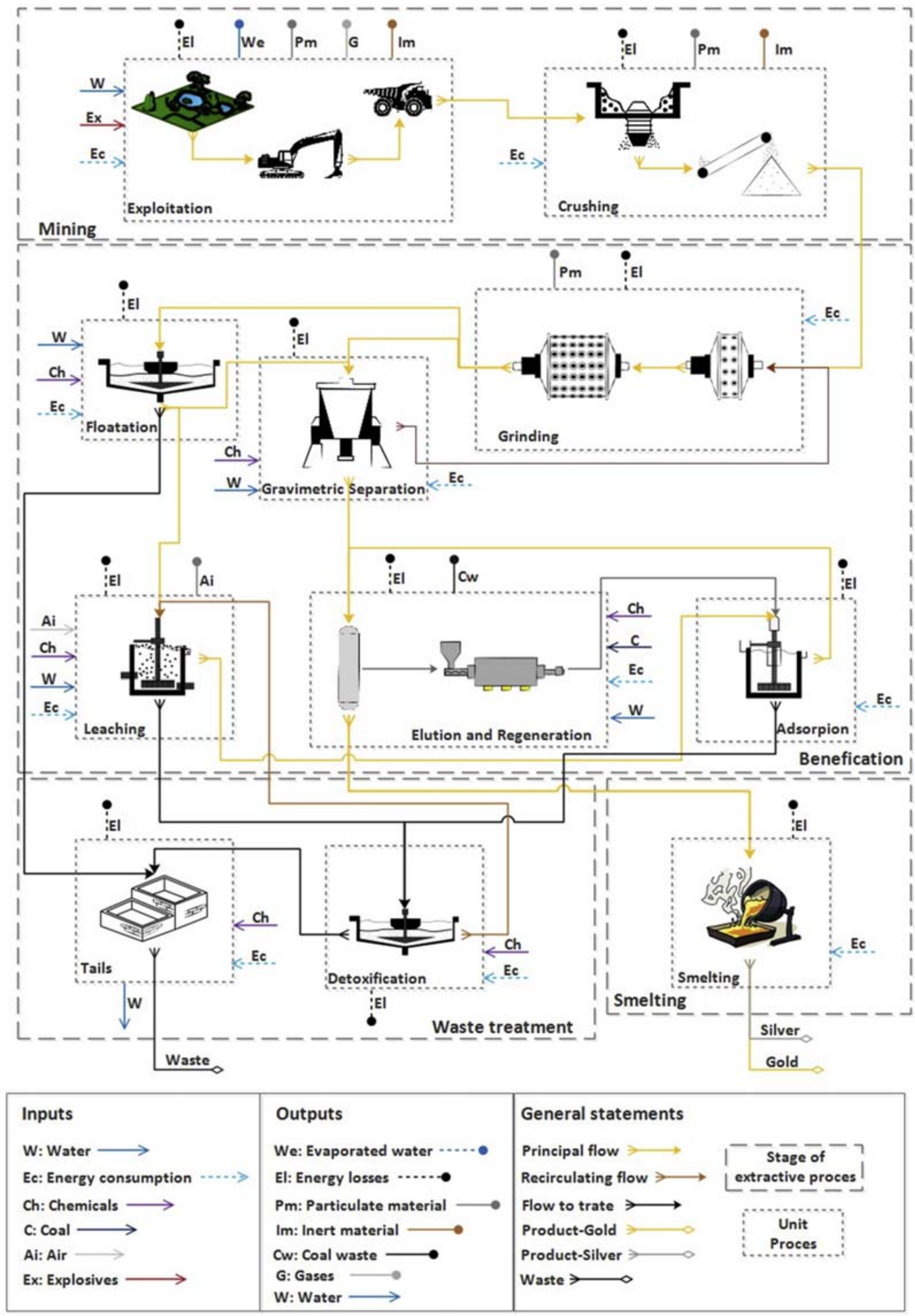

Fig. 1. Flow Diagram. Open-pit gold mining process.

All materials have a definable and calculable exergy content, with respect to a defined external environment. The consumption of natural resources implies destruction of organized systems and pollution dispersion, which is in fact generation of entropy or exergy destruction. Furthermore, exergy has the capability of aggregating heterogeneous energy and material assets. This is why the exergy analysis can describe perfectly the degradation of natural capital" [12].

Table 1. Exploitation Stage.

Process	Description	Input	Output
Stripping of topsoil	This consists of removing the capping soil or the topsoil in order to have access to the minerals and rocks, which are present in the subsoil.	– Diesel. – Organic material.	– Organic material deposited in the environment.
Mining	This makes mineral extraction, which are present in the subsoil (rocks), possible by means of the use of explosives and heavy machinery. This material or rocks are then moved to the primary crushing process.	– Water. – Explosives. – Electricity. – Diesel.	– Heat loss. – Water steam. – Particulate material. – Gases. – Inert material. – Rocks containing gold.
Crushing	In this process, the size of the rock coming from the extraction is reduced, to a size of 150 micrometers, in order to make its transportation and crushing management easy.	– Electricity. – Rocks and minerals with 0.00006% of gold.	– Heat loss. – Particulate material. – Inert material. – Crushed material.

2.1.1. The exergy of natural resources

In Table 6, Valero [12] summarizes the main methodologies used in order to calculate the thermodynamic properties of the most abundant minerals in the Earth's upper crust. Only the method is named, a consecutive number is given, and the maximum possible errors are given, which are associated to every method.

The ideal mixing model can calculate the exergy of the natural capital of the Earth's surface crust. This method is described by Equation (1) or the equation of a chemical solution of a solution, where “the error associated to the assumption of the mineral as a solid and ideal solution varies with the deemed mineral and diminishes with the chaos among the components, by assuming a maximum error of ±1%.” [12].

2.1.2. Chemical exergy of solutions

Chemical exergy is the work that can be obtained from a substance, which is at room pressure and temperature, if it reaches a state of thermodynamic equilibrium through chemical reactions or it can alternatively be defined as the minimum work necessary to produce a quantity of certain material from the substances present in the environment through reversible processes [4]. For practical purposes, the environment can be considered as a medium that undergoes internally reversible processes and does not experience variations in its properties. Szargut [4] and Valero [12] suggested a standard environment, by assuming a standard temperature and standard pressure and a number of substances, one for each chemical element. The chemical exergy of material, which is not a reference substance (the concentration of the material in the environment is unknown), can be calculated by selecting a reference substance for it. Where the chemical exergy can be expressed in the Equation (1):

$$\dot{b}_{mix}^{CH} = \sum y_i \, b_i^{CH} + R_u T_0 \sum y_i \ln(y_i) \qquad (1)$$

Table 2. Beneficiation Stage.

Process	Description	Input	Output
Grinding	This consists of reducing the rock to a size of 250 micrometers.	– Electricity. – Crushed material with 0.00008% of gold. – Recirculated material.	– Heat loss. – Particulate material. – Grinding material.
Gravimetric separation	This is a process, which consists of separating gold by gravity.	– Electricity. – Water. – Sodium hydroxide. – Sodium cyanide. – Grinding material with 0.00002% of gold. – Froth floating material with 0.00987% of gold.	– Heat loss. – Gravimetric separation material.
Froth floatation	This is when concentrated gold-containing Sulphur minerals are separatedfrom silicates and other minerals by means of chemical reagents.	– Electricity. – Water. – Flocculants.	– Heat loss. – Froth floatation material to leaching, gravimetric separation and to be treated in the tail process.

Table 3. Refining Process.

Process	Description	Input	Output
Leaching	Gold and silver are obtained by means of NaCN application. It is responsible for solving the metallic contents and producing a supplemented solution in gold and silver.	– Air. – Sodium cyanide. – Lime. – Water. – Electricity. – Floating material with 0.00194% of gold. – Recirculation flow of Detoxification.	– Heat loss. – Particulate material. – Material to be treated in the Detoxification and Adsorption process.
Adsorption	This process is based on the property that the activated coal has to obtain gold, which is contained in the cyanide solution.	– Electricity. – Activated coal. – Material resulting from leaching with 0.00194% of gold.	– Heat loss. – Material to be treated in the Detoxification process and the Elution process.
Elution and regeneration	The Elution process consists of the injection of NaOH and NaCN in order to extract gold and silver from coal and Regeneration consists of the removal of organic and inorganic material, which is adhered to coal during adsorption, by means of a thermic process.	– Water. – Coal. – Electricity. – Sodium hydroxide. – Sodium cyanide. – Hydrochloric acid. – Material resulting from a gravity separation with 31.07933% of gold. – Material resulting from Adsorption with a ratio of 50.43240%.	– Heat loss. – Coal. – Activated coal. – Current of material for casting. (This material contains a mixture of gold and silver known as electrum).

Table 4. Smelting Stage.

Process	Description	Input	Output
Smelting	Its objective is to carry out the selective precipitation of gold and silver contained in a solution resulting from elution by means of electroplating.	– Electricity. – Diesel. – Material resulting from elution, with 46.91645% of gold and the remaining percentage is silver.	– Heat loss. – Combustion heat. – Gold. – Silver.

where b_i^{CH} standard chemical exergy of i substance at reference condition P_0 and T_0.

2.1.3. *Composition of the mining deposit*

The composition of the mining deposit was established by combining the data provided by Rodríguez [18]. In his work, he determines the composition of the earth's crust in the State of Antioquia on the axis of the Colombian Andean Mountain Range, along with the production data of the mining activity (Case study), producing, as a result, Table 7. It shows the mass concentration of the mixture of substances (kg-substance/kg-mixture), which are extracted in the exploitation process and from which it is intended to separate gold as the main product and silver as a by-product.

Similarly, Table 7 shows the standard chemistry b_i^{CH}[kJ/mol] taken from the authors [4, 12] who in

Table 5. Waste Treatment.

Process	Description	Input	Output
Detoxification	The most toxic waste, derived from mining activity, is treated by means of a series of chemical reactions. Then, this waste is released into tail tanks.	– Electricity. – Lime. – Sodium peroxide. – Sodium metabisulphite. – Waste coming from leaching and adsorption.	– Heat loss. – Recirculation of material to leaching. – Waste.
Tails	This is a place where the whole production life's mining waste is deposited.	– Electricity. – Flocculants. – Detoxification and floatation waste.	– Waste, which is stored in large tanks. – Electricity losses in the form of heat. – Recirculated water.

Table 6. Summary of the methodologies used in order to calculate the thermodynamic properties of minerals [10].

Method	± Error %
Calculation of ΔH_f^0 or ΔG_f^0 from s^0	0
The ideal mixing model	1
Thermochemical approximation for sulfosalts and complex oxides	1
The method of corresponding states	1
The method of Chermak and Rimstidt for silicate minerals	1
The ΔO^{-2} method	1
The ΔO^{-2} method for hydrated clay minerals and for phyllosilicates	0.6
The ΔO^{-2} method for a different compound with the same cations	1
Assuming The ΔS, zero	5
The element substitution method	5
The addition method for hydrated minerals	5
The decomposition method	10

their work, establish reference status under an established methodology for substances present in the earth's crust. Similarly, a room temperature of $T_0 = 298.15$ K is set, and the universal gas constant as $R_u = 8.314472$ Kg/kmol K is taken. It is worth highlighting that chemical reactions are not taken into account in the case of the analysis, so that substances do not react with each other. They are only separated, so in the different mixtures of the process only their concentration is affected.

2.2. Exergy performance and other exergy indicators

Performance is, in general, the relationship between the benefit obtained and what has been done to obtain it, and performance provides information on how resources are consumed with respect to the amount obtained [2, 4]. Mathematically, the Exergy Useful Performance can be calculated by equation (2):

$$n_{B,I} = \frac{B_u}{B} \tag{2}$$

where $n_{B,I}$ is the exergy yield, B_u is the useful exergy of the resource obtained and B is the gross exergy. It is a general definition of exergy efficiency, but it is not necessary the unique indicator for assessing it for every process. Furthermore, even though many studies focused on the calculation of exergy efficiency claim to effectively measure the relationship between the transformed exergy and the consumed exergy of a process, a global view of the literature shows that the characterization of exergy performance is often open to interpretations, and in some cases, it is not well defined for certain operating conditions and specific equipment [2, 4].

Table 7. Elemental composition of the earth's crust for an open pit mining deposit, with standard chemical exergy [1, 10, 11].

Substance	Concentration	b_i^{CH}	Substance	Concentration	b_i^{CH}
SiO2	0.4991	1	TiO2	0.0073	24.7
Al2O3	0.1454	200.4	MnO	0.0016	119.4
Fe2O3	0.0907	16.5	H2O	0.0500	0.9
MgO	0.0783	62.1	Ag	$9.1x10^{-7}$	69.7
CaO	0.1116	110.2	Au	$5.41x10^{-7}$	51.5
Na2O	0.0161	296.2			

For the above and for the purposes of this investigation, since there is a mineral mixture which is going to be extracted or separated from its initial mixture, the definition of yield used by Velasquez [19] may be employed, as it proposes a relationship that compares the difference between the exergy of the separated substances and their initial mixture divided by the exergy resources invested for such a separation (3).

$$n_{B,II} = \frac{\sum B_{si} - B_{mix}}{Br} \tag{3}$$

where $\sum B_{si}$ is the exergy sum of separated substances, B_{mix} is the exergy of the initial mixture of substances and Br is a resource invested to separate the initial substance. The difference between useful exergy performance (2) and separation exergy performance (3) lies in their interpretation. The former focuses on the flow of useful exergy or the output of useful exergy compared with all input flow exergy in the processes, which is being analyzed, while the latter focuses on separation exergy compared with the exergy flow of supplies in each process.

In this paper, other indicators, which contribute to the interpretation of results, are used due to the complexity of the processes which are present in open-pit mining and high exergy flows, which occur during each stage. The first indicator (I_1) in equation (4) expresses the exergy of the outflow, which is a mixture of ore, gold, and water, compare with the exergy of the supplies, as shown below,

$$I_1 = \frac{Bu}{Br} \tag{4}$$

The second indicator (I_2) in equation (5) expresses gold exergy flow, which is extracted, and is present in a useful flow, where B_{Au} is the exergy of gold, which is either present or extracted in the mixture.

$$I_2 = \frac{B_{Au}}{Br} \quad (5)$$

This indicator concerns the amount of gold which is extracted in each process, while the indicator in equation (4) concerns the amount of ore which is processed per unit of supply required.

2.3. Exergo-economic analysis

An exergo-economic analysis is the one, which based on the exergy analysis the exergetic costs for each flow, in every process, is obtained. From the point of view of the procedures of modeling, simulation, and the optimization of energy systems, exergo-economic analysis basically adds two sets of equations: the exergetic cost balances for components/equipment or processes and the cost-splitting criteria based on exergy [20], which are performed in three steps:

- Step 1. Detailed exergy analysis.
- Step 2. Exergy costs.
- Step 3. Cost-splitting and exergo-economic assessment.

It is worth mentioning that the detailed analysis of exergy is achieved by implementing equation (1) in a traditional exergy balance for each process, which is described in Fig. 1.

2.3.1. Exergy-cost balance

The inflow exergy to any process is always higher than outflow exergy, due to the destroyed exergy. Therefore, the exergetic cost is understood as the actual amount of exergy required in order to obtain the product. It is important to highlight that this balance does not take into account the monetary costs of flows. Consequently, the exergetic cost is higher than the exergy content for each flow, in this way,

$$\textit{Exergetic cost } (K_i) > \textit{Exergy } (B_i) \quad (6)$$

The exergy-cost balance can be explained by the volume control of a process, by operating in a stable state.

Fig. 2 shows the Control Volume of a process in its inputs a, b, and c (water, fuel, electricity, raw material, etc.) and products e, f, and g (gold, water, mechanical power, etc.) so that the balance of exergetic costs is achieved, by using the following equation,

$$K_a + K_b + K_c = K_e + K_f + K_g \quad (7)$$

Equation (7) does not consider the destruction of the exergy because the exergetic cost of the product contains the inefficiencies of the system.

The exergetic cost of any flow (K_i) is related with its exergy content (B_i) by means of unitary exergetic cost, as showed in Equation (8),

$$k_i = \left[\frac{K_i}{B_i}\right] \quad (8)$$

When the equation for the unitary exergetic cost (8), is combined with the equation for exergetic cost (7), the Equation (9) is obtained,

$$(k_a)(B_a) + (k_b)(B_b) + (k_c)(B_c) = (K_e)(B_e) + (K_f)(B_f) + (K_g)(B_g) \quad (9)$$

Since Equation (9) is expressed in terms of the unitary exergetic cost and the exergy of each flow, when the unitary exergetic cost is not known, in order to solve Equation (9), the cost-splitting criteria must be taken into account.

2.3.2. Cost-splitting criteria

The cost-splitting criteria consists of giving defined values to unit exergetic costs based on the nature of the flow and its useful exergetic value for the process, thus:

- The output refers to the waste or the dumps of the process. Its unit costs is equal to zero. This is because the waste does not have any useful exergetic value.
- The supplies, which are extracted from natural resources, such as air, gravel, raw material, etc. are assess by their exergy content. Therefore, their exergetic cost is equal to 1.
- For the useful products, the Equality Method or the Extraction Method is set, where the Equality Method sets the computer, component, or analyzed

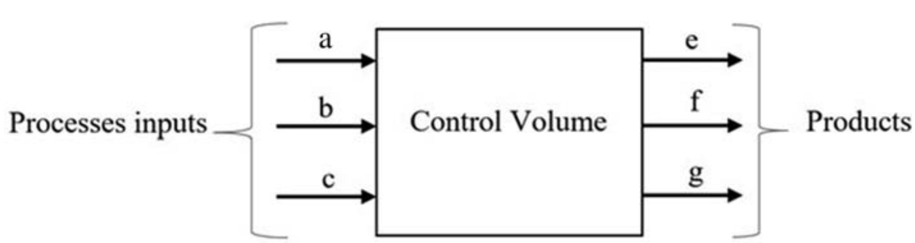

Fig. 2. Control volume for cost balance.

process, which must meet all exergy demands and, consequently, all products have the same average cost of exergy. The extraction method states that the equipment, component, or process studied has a single function and the product of this function takes care of its capital, operational, and maintenance costs. In this way, the user of this product will pay for the spent exergy rate.

3. Results and discussion

In this chapter, the results obtained after the exergy analysis will be shown in four sections: the first talks about the balance of exergy in each stage of the process. The second deals with the results obtained, by applying the exergy performance and indicators for each process involved in the extractive activity. The third shows the results obtained in the analyses of the extractive activity and a sensitivity analysis, which aims to outline how overall mining activity performance is affected if gold production increases, by using the same supplies and assuming a higher gold concentration in the extracted material. The fourth part shows how the global exergy performance is affected, if the mining activity is carried out selectively by decreasing the amount of material removed. Finally, the exergetic cost of the currents is calculated.

Equation (1) is used for the calculation of the substance mixture exergy. The exergy balance was calculated by using the concept of the Chemical Exergy of Solutions with a focus on the mineral capital in earth and the state of reference proposed by Valero [12] combined with the methodology and reference state proposed by [4, 21].

3.1. Exergy balance

This item shows general exergy balance during each stage of the process. In Table 8, the exergy balance is shown with its input, output, and destroyed exergy. The input is divided into two parts: the flow that contains gold and the flows that are considered as supplies (water, chemical substances, electricity, diesel, and others). The output exergy is divided into two parts: the useful flow and waste flow. The last column of Table 8 shows the exergy destroyed in each process, and the last line shows the overall balance, by taking as control volume all the processes involve in gold production.

It should be emphasized that in some cases the useful flow does not contain gold, but it still has a value for the plant, either through obtaining water, activated charcoal, or others. Another caveat is found in the overall balance since its values do not correspond to the sum of the unit analysis: this is because of the recirculation and recovery of flows, which are present within the plant. Thus, the water used by Froth Floatation is an input for the unitary process, but it is waste recovery for the plant. Another important aspect is the generated waste since for mining and crushing cases this could be taken as destroyed exergy because they are minerals with exergy content and they are accumulated without any use, so this exergy, as long as it is not useful, will remain as waste in the unit balance or destroyed exergy in the global balance.

The processes in Table 8 for interpretation purposes could be divided into two: mechanical separation processes (^{m}) and chemical separation processes (^{ch}). The former are those which predominantly do the mechanical work in order to fulfill their function, and the latter are those in which the use of chemical solutions are used to separate or to obtain gold.

Some aspects to highlight of Table 8 are the large exergy flows of an order of magnitude of up to 107 kW. Another aspect to consider is the mechanical separation processes (^{m}), where the largest amount of extracted material is separated.

Table 8. General exergy balance of open-pit mining, ateach stage [kW].

Processes	Exergy Input		Exergy Output		Destroyed Exergy
	Main flow	Supplies	Useful flow	Waste	
Stripping of topsoil a	1454	12515	1454	-	12515
Mining^{m}	1529160	44285	683972	845509	43965
Trituration	683972	2481	529635	154380	2438
Crushing^{m}	1042712	99971	1052597	-	90086
Gravimetric separation^{m}	522070	13315	513145	-	22240
Froth floatation ^{ch}	530672	10465	29209	504915	7013
Leaching ^{ch}	29063	3767	19260	12695	874
Adsorption ^{ch}	19260	3144	2807	19337	260
Elution and regeneration ^{ch}	2875	2461	2889	1201	1246
Smelting ^{ch}	0.58	296	0.6	-	296
Detoxification and tails ^{ch}	538148	169986	75241	532416	100477
Global balance	1530614	284557	0.6	532416	1282754

In the smelting process, the low flow of material to be melted is appreciated, with as an exergy content of 0.58 kW, while the extracted material has an exergy content of 1529160 kW, which means that the remaining material ends up in tailing ponds.

The high flow of exergy destroyed, along with the system waste in the overall balance, when compared with the useful flow shows high system inefficiencies. Thus, indicating with this that most system input ends up as destroyed exergy and waste.

Fig. 3 shows the balance of exergy in global terms, whose calculation basis is given by the sum of the input (1815172 kW), this amount of exergy is distributed in gold, silver, waste of the process and destroyed exergy. It is important to highlight that the products (gold and silver) only represent the 0.07% of the input exergy of all the inflow exergy.

Fig. 4 shows the Grassmann Diagram in terms of the unit process of the open-pit mining process, which is based on the input of the system (1815172 kW) being 100%. The useful flows are 0.16 kW for gold and 0.45 kW for silver; these flows are so small that they are not clearly seen in the Figure. In this case, supplies contain recirculated water, which is obtained from detoxification and tails. Also, it can be observed that the greatest amount of exergy comes from the extracted material. Since the ultimate goal is to separate gold and silver and because their exergy is very low, the destroyed exergy within the processes is very high. The waste flow as accumulated material could be considered as destroyed exergy, because it is stored in large tailing ponds. In this way, the destroyed exergy of the system is almost comparable to the entries.

Fig. 4 shows what is reflected in Table 7 and graphically reinforces the above, where mechanical separation processes are the ones which process the largest exergy flow, while chemical separation processes move a lower amount of flows. Similarly, it is shown that the largest amount of exergy comes from the extracted material (84.24%), which is mostly wasted in the mining process (49%) while the other part is maintained until the floatation process, which ends up in detoxification and tails (27.82%).

The water recirculation obtained in the detoxification process is considered a useful product and it is reused as a supply in some processes. Thus, this overall performance does not leave the system and, in unitary terms, it is taken into account as a supply forthe processes which consume it. It is worth mentioning that the size of the arrows in the Grassmann Diagrams is a representation of the magnitude of the flow, but in some cases, this size was modified, so that they were visible because of their low values compared to others.

As a practical and illustrative example for the balance of both global and unitary exergy, the mining process is considered as an input and output flowchart, which is illustrated in Fig. 5.

On the right side of Fig. 6, the entries are divided into two groups: Supplies and the Main Flow. Whereas, on the left side of the same Figure, there is the output and the destroyed exergy, which correspond to the useful flows and waste in Table 8.

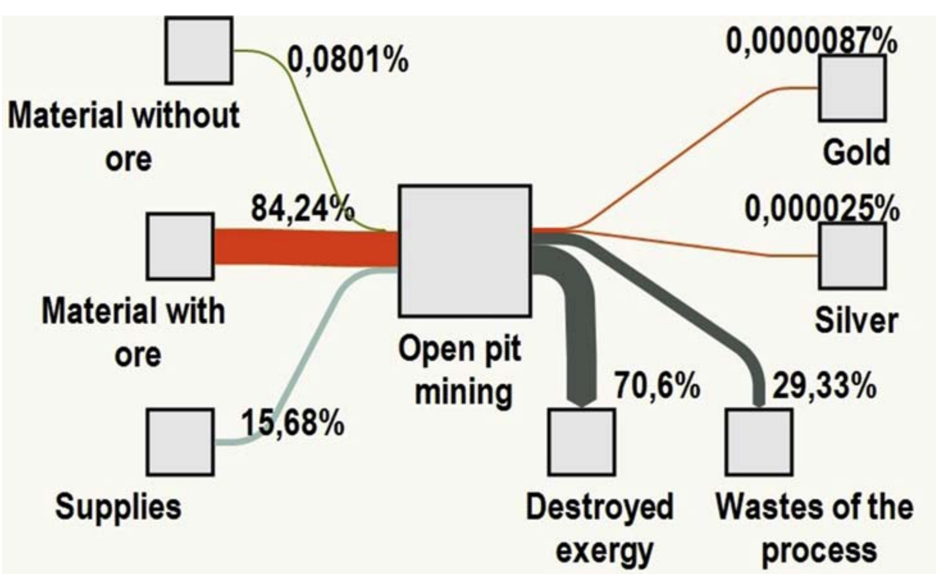

Fig. 3. Global balance in Grassmann Diagram [kW].

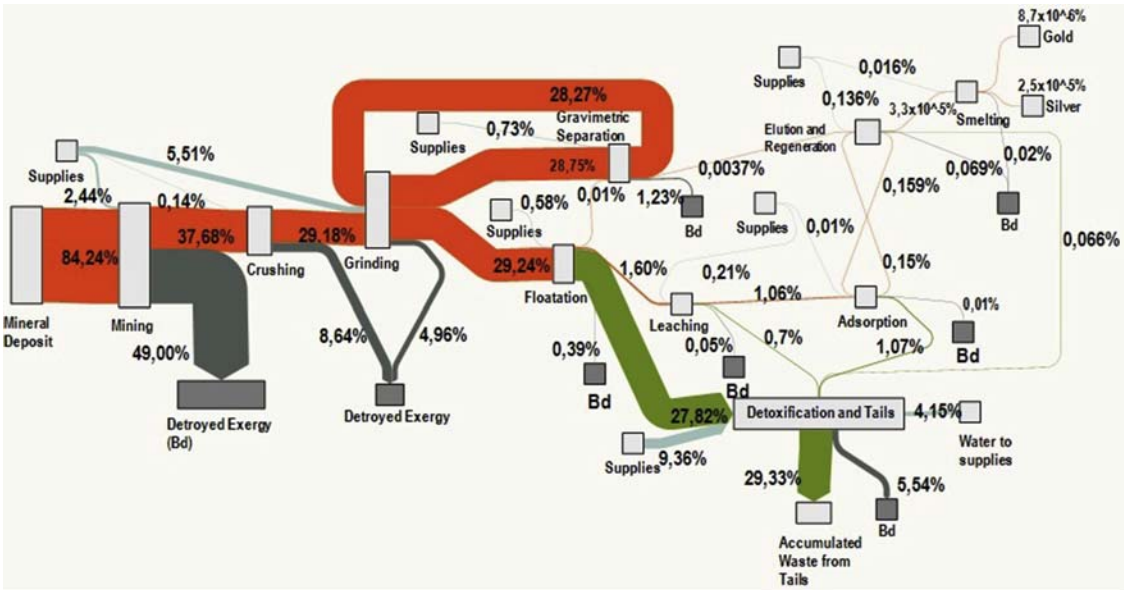

Fig. 4. Unit process balance in Grassmann Diagram.

Exergies in Table 9 were calculated by using Equation (1) and a traditional exergy balance. The purpose of this example is to clarify the different exergetic currents, which can intervene in each unit process, so something similar happens for the other processes. It is worth mentioning that in the mining plant there is water recovery and flow recirculation, so the output of one process can be, subsequently, converted into an input for another process. It is also emphasized that the destroyed exergy is not an output from the system.

Therefore, when characterizing the input and output flows, the destroyed exergy of the system can be calculated, by using the exergy balance shown in the following equation:

$$(B_{input}) = (B_{output}) + (B_{destroyed}) \tag{10}$$

Thus, culminating with the exergy balance in each process.

3.2. Exergy performance for each processes in open-pit mining

Table 10 shows the exergy efficiency and process indicators, which is calculated for gold ten or corresponding to 0.54 g/t of the input material, for gold production of 0.26 g of gold/t of the extracted material. The Useful Exergy Performance ($n_{B,I}$) compares the exergy of the useful flows in the output of each process in relation to the input (flow of processes and supplies, See Table 8). The difference corresponds to the percentage of destroyed exergy and the flows, which are considered as waste. It can be observed that in physical separation processes, such as gravimetric separation, crushing, and trituration, the useful flow still contain a largest amount of useful exergy.

The Separation Exergy Performance ($n_{B,II}$) shows how the processes use the supplies in order to

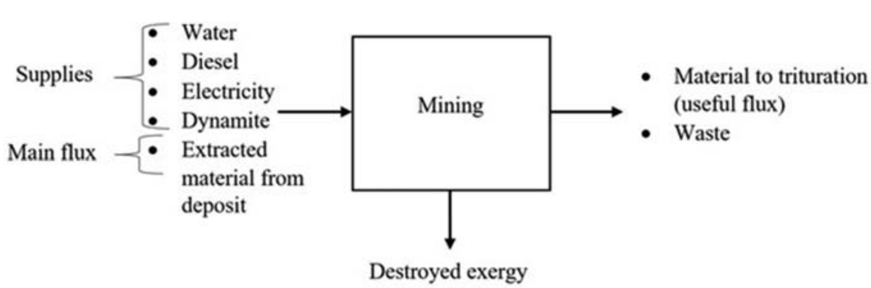

Fig. 5. Mining diagram input and output.

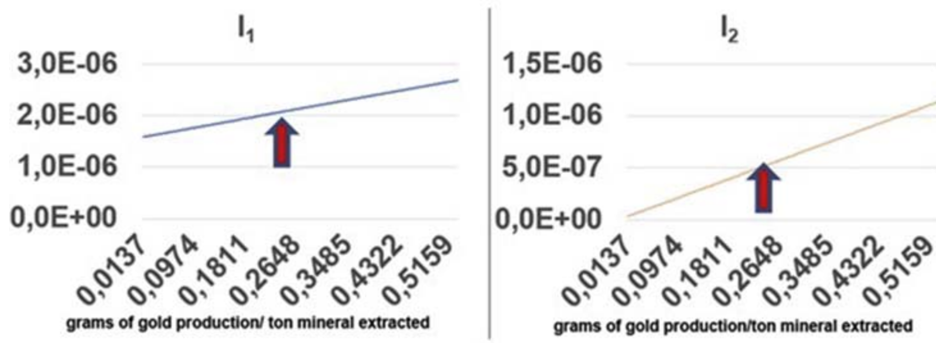

Fig. 6. Comparison between I_1 and I_2, by using the same input and extracting more gold.

concentrate gold and silver. It maybe a better exergy indicator in the separation process. In the physical separation processes, the value of $n_{B,II}$ is low in relation to $n_{B,I}$, which indicates that it could make better use of the exergy of the supplies. In general, chemical separation processes, such as leaching, adsorption, and elution, make better use of resources.

The physical processes (^{m}) are good at processing the main current, but they are inefficient at separating extracted material. In other words, these processes destroy exergy to move or resize the extracted material. In the overall balance Useful Exergy Performance is 3.37×10^{-5}% and Separation Exergy Performance is 1.11%. This indicates that in open-pit mining, the process seems to be very inefficient given the low value of both indicators, and this is a strong reason to study its economic feasibility.

Another aspect that can be highlighted in Table 10 is that Useful Exergy Performance shows better behavior for physical separation processes (mining, trituration, crushing, and gravimetric separation). While for floatation, leaching adsorption, and detoxification tails, which are chemical separation processes, Separation Exergy Performance has better results. This is because of the large amount of extracted material which needs to be processed.

The process flows, which are a mixture of inert materials, gold, and silver, have very high exergy contents, which can alter the evaluation of the exergetic performance of the processes. Therefore, the I_1 and I_2 indicators are proposed. Where indicator 1 shows the comparison between useful exergy in each process and the supply, while indicator 2 shows the comparison between gold flow exergy, which was separated in each process, and its supply. These new exergetic indicators are a tool to illustrate what happens in the extractive activity because of the difficulties of calculating the efficiency of the extractive activity due toits complex flows and mixtures. Table 9 shows both indicators. In some processes, these indicators do not apply because even if they generate a useful current, they do not necessarily generate gold, such as in the case of detoxification which reuses water, but is unable to recover gold. Based on the outcomes of the I_1 and I_2 indicators, in general, it can be concluded that the amount of resources invested is high in order to separate gold and silver from the ore.

Something which both chemical separation (ch) and mechanical or physical separation (m) have in common is that in each case indicator 2 is very low (10^{-6}), which shows inefficient exergetic processes when separating gold from the mixture.

It can also be seen at the button of Table 10 the overall balance of open-pit mining the Useful Exergy Performance (3.37×10^{-5}%) is lower than the Separation exergy Performance (1,11), which shows that open-pit mining is a process that meets its goal

Table 9. Balance of the mining unit process.

Input		Exergy kW	Output	Exergy kW	Destroyed exergy
Supplies	Water.	8047	Material to trituration.	683972	
	Diesel.	32155			
	Electricity.	2560	Waste.	845509	
	Dynamite.	1521			
Main flow	Extracted material from the deposit.	1529160			

Table 10. Comparison between useful exergy performance and separation performance in each process of the mining activity.

Processes	$n_{B,I}$ (%)	$n_{B,II}$ (%)	I_1	I_2
Mining[m]	43.47	0.72	15.44	4.71×10^{-6}
Trituration[m]	77.16	1.71	213	8.41×10^{-7}
Crushing[m]	92.12	9.89	10	7.00×10^{-9}
Gravimetric separation[m]	95.85	8	38	1.50×10^{-8}
Froth floatation [ch]	5.40	32.989	2.7	2.24×10^{-6}
Leaching [ch]	58.67	76.78	5.11	1.01×10^{-7}
Adsorption [ch]	12.53	91.72	0.8	4.89×10^{-6}
Elution and regeneration [ch]	54.15	49.38	1.17	6.41×10^{-5}
Smelting [ch]	0.21	0.01	0.002	5.34×10^{-4}
Detoxification and tails [ch]	10.63	40.89	0.16	-
Overall balance	3.37×10^{-5}	1.11	2.15×10^{-6}	5.54×10^{-7}

of gold separation, but their efficiency values are very low, which is a strong reason to study its economic viability in further studies.

3.3. Overall performance and sensibility analysis

This section aims to show the changes associated with having a higher content of gold in the original material, which results in higher gold production with the same material and energy input. In other words, it intends to show the change in exergy yields, compared with the current stage of the mine, and if it produces more gold with the same input by examining other possible conditions of the gold content present in the soil. Fig. 7 illustrates the comparison between I_1 and I_2 in the overall mining activity, by assuming that more gold could be extracted by using the same input. For such an assumption, the minimum operable concentration required is 0.0137 kg gold/t ore and the maximum possible operable concentration is 0.5159 kg gold/t ore.

In Fig. 6, the red arrow shows the operation conditions of the mining plant. If it were possible to

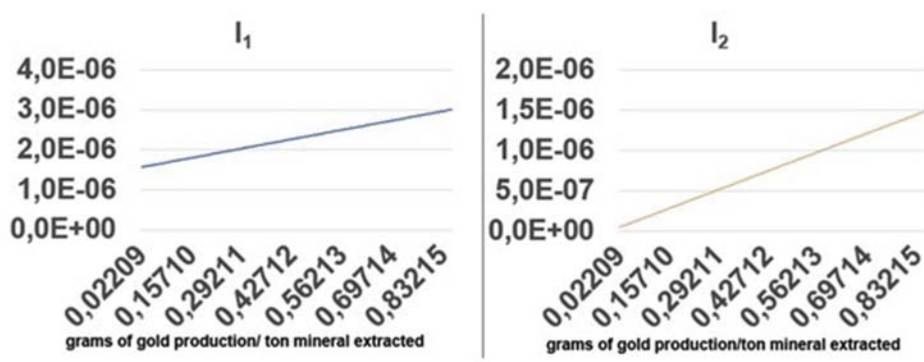

Fig. 7. Comparison between I_1 and I_2, selecting the gold veins of the ore.

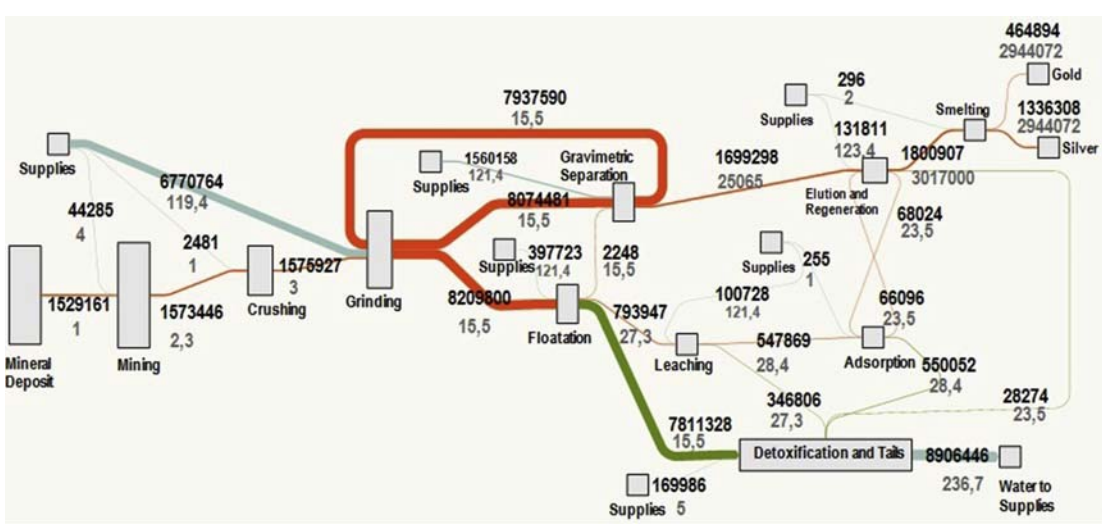

Fig. 8. Flow of Exergetic Cost and Unitary Exergetic Cost per unit processes [kW].

extract larger amount of gold per tonn of material processed, by using the same resources, there would not be an appreciable change in the indicators I_1. It is worth mentioning that the sensitivity analysis is only applied to the global balance of the mining process. In the second graph of Fig. 6, the indicator I_2 show that if the amount of gold produce increas there would be a reduction in the processing of largeamount of the extracted material in order for them to be separated into gold ingots. If this could be done, the extracted material would be reduced by 40% and, therefore, the consumption of supplies would decrease by 25%.

Table 11. Unitary exergetic cost of each flow.

Processes	Inputs	k	Des.	Outputs	k	Des.
Mining	Water	1	Supp	Main flow^{T}	2.3005	Cal
	Diesel	1	Supp	Waste	0	WE
	Electricity	1	Supp	-	-	-
	Dynamite	1	Supp	-	-	-
	Main flow	1	NR	-	-	-
Trituration	Main flow^{T}	2.3005	Cal	Main flow^{C1}	2.9755	Cal
	Electricity	1	Supp	Waste	0	WE
Crushing	Main flow^{C1}	2.9755	Cal	Main flow^{F1}	15.4706	Cal
	Main flow^{C2}	15.4706	Cal	Main flow^{G1}	15.4706	Cal
	Agua	118.3711	Cal	-	-	-
	Electricity	1	Supp	-	-	-
Gravimetric separation	Main flow^{G1}	15.4706	Cal	Main flow^{E1}	25064.8497	Cal
	Water	118.3711	Cal	Main flow^{C2}	15.4706	Cal
	Chemical	1	Supp	-	-	-
	Chemical	1	Supp	-	-	-
	Electricity	1	Supp	-	-	-
	Main flow^{G2}	15.4706	Cal	-	-	-
Froth floatation	Main flow^{F1}	15.4706	Cal	Main flow^{L}	27.3178	Cal
	Water	118.3711	Cal	Main flow^{G2}	15.4706	Cal
	Chemical	1	Supp	Flow to Tails^{1}	15.4706	Cal
	Electricity	1	Supp	-	-	-
	Chemical	1	Supp	-	-	-
Leaching	Main flow^{L}	27.3178	Cal	Main flow^{A}	28.4456	Cal
	Electricity	1	Supp	Flow to Tails^{2}	27.3178	Cal
	Chemical	1	Supp	-	-	-
	Chemical	1	Supp	-	-	-
	Water	118.3711	Cal	-	-	-
Adsorption	Main flow^{A}	28.4456	Cal	Flow to Tails^{3}	28.4456	Cal
	Coal^{E}	23.5466	Cal	Main flow^{E2}	23.5466	Cal
	Electricity	1	Supp	-	-	-
Elution and regeneration	Main flow^{E1}	25064.85	Cal	Main flow^{F}	3017000.042	Cal
	Main flow^{E2}	23.5466	Cal	Flow to Tails^{4}	23.5466	Cal
	Electricity	1	Supp	Coal^{E}	23.5466	Cal
	Chemical	1	Supp	-	-	-
	Chemical	1	Supp	-	-	-
	Chemical	1	Supp	-	-	-
	Water	118.3711	Cal	-	-	-
	Coal	1	Supp	-	-	-
Smelting	Main flow F	3017000.04	Cal	Gold	2944072.892	Cal
	Electricity	1	Supp	Silver	2944072.892	Cal
	Diesel	1	Supp	-	-	-
Detoxification and tails	Flow to Tails^{1}	15.4706	Cal	Recovered water	118.3711	Cal
	Flow to Tails^{2}	27.3178	Cal	Waste	0	WE
	Flow to Tails^{3}	28.4456	Cal	-	-	-
	Flow to Tails^{4}	23.5466	Cal	-	-	-
	Electricity	1	Supp	-	-	-
	Chemical	1	Supp	-	-	-
	Chemical	1	Supp	-	-	-
	Chemical	1	Supp	-	-	-
	Chemical	1	Supp	-	-	-

Cal: Calculated Value. Supp: Supplies. NR: Natural Resource. WE: Waste Environment. Superscript ^{i}: same flow.

Fig. 7 shows the results of the sensitivity analysis when the gold tenor in the vain increases. It can be concluded that although the gold content is increased by reducing the inert material and supplies, there is no meaningful changes in the I_1 and I_2 indicators, which shows that the consumption of exergy is very high and that the processes are not sensitive to gold content in the ore. By comparing the aforementioned results, it can be stated that it does not matter if gold extraction is increased or the input is reduced, by applying selective mining, the process continues to show Indicators of the order of 10^{-6}.

3.4. Exegetic cost of plant flows

Fig. 8 shows the results of the equations of the exergy cost balance of the main flows of the plant, which are indicated in bold in the graph. By comparing the exergetic cost of the supplies, with exergy content amounting to 214691 kW, with respect to the exergetic cost of the produced gold and silver, evaluated at 1801202 kW, a significant increase can be seen due to the irreversibility of the process.

When the analysis is carried out in terms of unitary exergetic cost, shown in gray in the graph, it can be observed that there is a significant increase in the unitary exergetic cost of the products. By Comparing the unitary exergetic cost of supplies, whose value is 1, in relation to the unitary exergetic cost for gold and silver, whose values come up to 2,944,072, the increase due to inefficiencies in all processes is evident.

Table 11 shows the unitary exergetic costs of each flow as explain in Section 2.4. By showing the input and output for each process. This table complements the results shown in Fig. 8. It can be appreciated that the value of the unitary exegetic cost of supplies equals 1. As gold and silver go through every stage of the plant there concentrated and the unitary exergetic cost increases until the rich the maximum value for both.

Since the cost sharing method was used, in some cases, the unitary exergetic cost of some flows is equal, as in the case of gold and silver. Similarly, it happens with water reclamation, since it comes from the same place, and as the same unitary exergetic cost.

4. Conclusions

Based on the input exergy of the system (1815172 kJ/s), the useful flows of exergy are 0.16 kJ/s for gold and 0.45 kJ/s for silver. These flows are so small that they show the inefficiency of open-pit mining.

The Useful Exergy Performance that compares the exergy of the useful flows in the output of each process in relation to the input, shows better behavior for the physical separation processes, such as gravimetric separation, crushing, and trituration because they retain the largest amount of useful exergy.

The Separation Exergy Performance shows how the processes use the supplies in order to concentrate gold and silver, and it shows better behavior for the chemical separation processes, such as leaching, adsorption and elution, as it makes better use of the resources.

Open-pit mining appears to be very inefficient because, in the overall balance, the Useful Exergy Performance is 3.37×10^{-5}% and the Separation Exergy Performance is 1.11%. Since these values are too low, they serve as a starting point for studying open-pit mining's economic feasibility.

Based on the I_1 and I_2 indicators, it can be concluded that the amount of resources invested is high in order to separate gold and silver from the mine, and the open-pit mining produces a large amount of destroyed exergy, which makes it very inefficient.

The sensitivity analysis does not show a noticeable change in the efficiency of the process when the content of gold and silver in the mine is changed.

The result for the unitary exergetic cost obtained for gold and silver is 2944072 kJ/kJ.

Conflict of interest

None declared.

Ethical statement

Authors state that the research was conducted according to ethical standards.

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