SUSTAINABLE DEVELOPMENT OF GEM PRODUCTION: AN ANALYSIS USING THE ANALYTIC HIERARCHY PROCESS

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ABSTRACT

The gems, jewelry, and precious metals sector is essential for developing regions with this activity and there is a high degree of informality in the mining and trading gemstone sectors. The present study analyzed data from the production process of precious stones in the Brazilian national market. We identified the importance of the factors contributing to the quality of the gemstone production process concerning mining, cutting, and marketing, under the scope of sustainable chain development. A list of references was used to select thirteen significant factors in the precious stone production process that contributed to the sustainable development of the chain related to mining, cutting, and marketing. We used a multicriteria decision model applying the Analytical Hierarchy Process (AHP) to consider the degree of importance of the production stage process of gemstones and the factors that impact the sustainable development of the production chain. In applying the model to the production stages, the criteria and sub-criteria factors were considered. The results suggest that sustainable development is highly related to gem mining (44.7%, rank 1), moderately related to gem cutting (32.5%, rank 2), and there is little relationship to gem marketing (22 .8%, rank 3), considering the criteria, sub-criteria, and alternatives. The requirement related to the technical qualification and skill of the lapidary is the most critical factor in the production process. The second most important factor is commercialization, followed by the preservation of the mining area and the valuable life of the mine.

Keywords: regional development; semi-precious gemstone; mining; sustainability; supply chain; opal production

1. Introduction

Brazil is recognized for its mineral wealth and variety of gems. The gems, jewelry, and precious metals sector in the country has a high degree of informality in the segments of mining and marketing precious stones. The exploitation of Brazilian mineral activity is essential for developing some regions, despite numerous criticisms regarding its predatory nature (Ribeiro, 2011). Changes in the national and international context have forced organizations to innovate, manage change and promote the sustainable development of their products or services.

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The emergence of the concept of sustainability reflects a transformation in global thinking that forces organizations to reconsider how their activities are developed to boost economic development, reducing the negative impacts on the environmental, social, and economic dimensions of the production of goods and services (Alves, 2020). This scenario presents challenges for the mineral sector, increasing the complexity of extraction, production, and commercialization. The complexity is due to the interaction between different aspects such as economic factors, environmental and social issues, and government regulations. Thus, it is up to the sector to develop strategies to improve quality and services that meet sustainability requirements (Arango-Aramburo et al., 2017). Sustainable development is a continuous process that integrates activities in the economic scope, ensuring economic growth; in the social aspect, taking care of the worker in the work environment and the development of the community; and with the environmental elements, ensuring the protection of natural resources and the environment (Dubinski, 2013). However, the current literature did not use the triple bottom line approach to identify a vision of sustainable development in the gem mining sector.

Thomas Saaty developed the AHP in 1990. It offers a system where one can arrange the data of a problem in a hierarchical and judgment-based way and establish priorities for decision making (Camanho & Moraes, 2007). Several academic studies and applications present AHP as a multicriteria decision system that can help production systems (Reis et al., 2017; Saaty & Shang, 2011; Reck & Schultz, 2016; Wang et al., 2019). Periaiah et al. (2021) underlined the consequences of bauxite mining on the environment through the impacts of the environment, ecology, and economy using multicriteria analysis. Shen et al. (2015) investigated an appropriate implementation approach of green supply chain management practice in the Indian mining sector using the AHP.

Due to the importance and complexity of the gem mining sector in Brazil, the present study aimed to evaluate the extent of factors contributing to Brazil's sustainable gem production process. In the past decade, there has been increasing discussion about the necessity to shift modern mining to a more sustainable framework, with many mining companies now reporting annually on their sustainability performance alongside their financial results (Shen et al., 2015). Bui et al. (2017) proposed an indicator-based sustainability assessment framework to assess the sustainability of the mining sector on a national and global scale. Sauer & Seuring (2017) conducted a systematic literature review on sustainability in mineral supply chains and suggested adopting practices for improving sustainability in the mineral supply chain. The present study focuses on sustainable development issues in the gem mining context and provides suggestions for the decision-making of regional policies. We considered the economic, social, and environmental components (triple bottom line) of this process, in a regional aspect, respecting the drive of the production chain, available human resources, technologies, legislation, and institutions that support the mining activity. We also verified if the selection presents relevant results for decision-making that leads to sustainable development for the gem production process. Thus, the study sought to interpret the interdimensional relationships of the gem production chain to guarantee the process results are within the scope of sustainable development applying the Analytic Hierarchy Process (AHP).

2. Background

2.1 Gems production chain overview

The union is responsible for organizing the administration of mineral resources, the mineral production industry, and the distribution, trade, and consumption of mineral products (Brasil, 2018). The production of Brazilian gems is concentrated in the states of Minas Gerais, Rio Grande do Sul, Bahia, Goiás, Pará and Tocantins (Ribeiro, 2011). The performance of the gems, jewelry, and precious metals sector decreased 7.3% in terms of the number of organizations. Direct jobs dropped by 5.9% between 2015 to 2017 when observing the wholesale trade jewelry, watches, jewelry including cut precious and semi-precious stones, gem extraction (precious and semi-precious), and gem cutting (IBGM, 2018). According to the Brazilian Institute of Gems and Precious Metals (IBGM) (IBGM, 2018), commerce is the segment that employs the most people, followed by mining and then the polishing industry. This indicates the low level of transformation of the products present in the supply chain. The production chain includes mining, polishing, production of stone artifacts, the jewelry and veneer industry, jewelry, raw materials, and equipment used in the production process, in addition to activities related to design (Ribeiro, 2011). The Ministry of Mines and Energy (MME) considers the production chain of gemstones linked to the jewelry and mineral handicraft sector, represented by the following four aspects:

a) The mining and all materials and services used in the extraction of rough stone;
b) The stone cutting and artifact industry, encompassing the production of cut stones, handicrafts, and stone artifacts;
c) The jewelry and costume jewelry industry, responsible for the production of gold, silver, veneer, and ordinary metal jewelry; and
d) The commercialization, both in the domestic and foreign markets.

Mining and cutting are the links in the chain that present the greatest informality and face significant obstacles to development and are considered declining activities. Although the other links have low global participation, they already have greater competitiveness and organization due to the qualitative gains in design and valorization of the national product (Ribeiro, 2011). Gems can play a symbolic force towards rebuilding the tarnished image of post-conflict areas. Conflict regions that previously led to negative marketing of gem brands can, over time, be modified into post-conflict development opportunities and lead to positive brands (Makki & Ali, 2019).

2.2 Mining

The mining activity contributes to economic and social development by supplying essential minerals for the development of industries, increasing jobs and services and technological progress, which positively impacts the well-being of the population and the economical functioning of the global economy. However, negative impacts are also found in the mining activity, such as labor diseases related to mining activities, the effects on the landscape, changes in the course of rivers, unemployment, social conflicts, which sometimes occur even after the closure of the mines (Alves et al., 2020; Arango-Aramburo et al., 2017). Mining activities face complex problems through the interaction of many different interests of stakeholders including companies, legislators, regulators, the local population, illegal miners, and a global market. These parties are inserted in a context of interdependence characterized by high uncertainty, fluctuating price and demand, fluctuating rules, and unpredictable environmental and social consequences (Arango-Aramburo et al., 2017).

The environmental impact caused by gemstone mining is considered simple compared to other types of mineral mining since it does not use chemicals and is often restricted to small areas. The most common impacts highlighted in the literature are deforestation, water pollution, siltation of rivers, and landscape alteration caused by ditches, holes, and tunnels (Milanez & Oliveira, 2013). To mitigate potential impacts from mining activities, organizations must adopt sustainable development strategies related to the environment and society such as conceptualizing sustainability, adopting methods for sustainable development of products and services, supporting companies in their sustainability efforts, and emphasizing the importance of effective communication (Alves et al., 2020). Public agencies could develop programs that encourage miners to create new products using waste products (MME, 2018).

Technological advances in the mining sector decrease pollution, production costs, and productivity making the process more efficient. In addition to technological advancement, mining must be concerned with price, usually the main uncertainty linked to the activity (Arango-Aramburo et al., 2017). The promotion of associative entrepreneurship in mining improves the relationship of the agents involved with the government. It allows miners to accumulate the financial capital necessary to obtain a cleaner and more productive technology (Saldarriaga-Isaza et al., 2013). With the increase in jobs created, social conflicts tend to decrease, which leads to a rise in attractiveness. Other factors can also make the sector more attractive, for instance, advancements in infrastructure, security, legal stability, and political stability in the country (Arango-Aramburo et al., 2017). In Brazil, the activity of mineral extraction is regulated by the Mining Code. This Code governs the regimes for the extraction of mineral resources, shown in Table 1 (Brasil, 2018).

Table 1
Rules for the use of mineral resources in Brazil

Rule	Description
Rule of concession	Depends on the Ordinance of the Minister of State for Mines and Energy or when granted by the National Mining Agency (ANM) if it has as its object the mineral substances referred to in art. 1 of Law No. 6567 1978.
Rule of authorization	Depends on license issuance by ANM.
Rule of licensing	When dependent on a license issued in compliance with local administrative regulations and registration of the claim with the ANM
Mining permit rule	Depends on license issuance by ANM.
Monopolization rule	As a result of a particular law, it depends on the direct or indirect execution of the federal executive branch.

Source: Brasil (2018)

National interest and public utility are fundamental for the development of mining. Mineral deposits are characterized by their locational rigidity, which expresses the restriction in selecting areas to implement the activity to generate lesser environmental impacts. They are finite and have economic value. The mining activity includes research, mining, mine development, processing, commercialization of ores, use of tailings and waste, and mine closure (Brasil, 2018). The determination of the mine size made by the ANM considers the annual mineral production to define its category (Table 2). Artisanal mining, in turn, constitutes a portion of mining characterized by the use of traditional and inefficient technology and by poorly qualified labor, almost always practiced in independent units, often informal, without titles or licenses, following a business model family and subsistence. Most cases involve micro and small mining operations, but there are situations that involve medium-sized or even large-scale mining operating artisanal (MME, 2018).

Table 2
Mining operation category and production

Category	Annual production
Large mine	≥ 1 million t/year
Mina média	100 thousand to 1 million t/year
Small mine	10 thousand to 100 thousand t/year
Micro mine	≤10 thousand t/year

Source: MME (2018)

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Although battled by the government, illegal mining often occurs. The formalization of mining activity must be considered a priority for the sector. One way of tackling informality is issuing formal property titles that bind the miner to the land. Land title ownership results in avoiding evasion and discouraging the practice of inefficient transient mining and the degradation of the environment (Milanez & Oliveira, 2013). The informality of artisanal and small-scale mining leads to a reduction in industry contributions to local development, which causes an impact on the economy through underreporting and underestimating production and eliminating formal resources economy through tax evasion. In addition, informality tends to influence inappropriate environmental, social, and labor practices and perpetuate social conflicts and corrupt regimes in certain countries (Makki & Ali, 2019).

2.3 Gem-cutting

India, China, and Thailand are lapidary centers and dominate the jewelry-making industry. Colombia, Sri Lanka, and Asia also benefit from the gems industry to substantiate sustainable livelihoods for economic growth (Makki & Ali, 2019). In Brazil, the main polishing poles are located in São Paulo, Minas Gerais, Rio de Janeiro, and Rio Grande do Sul. In some cases, the gems exported in a raw state are polished in specialized workshops in other countries and return to Brazil with values higher than those for which they were marketed (MME, 2018).

The use of rudimentary polishing techniques and the scarcity of skills in processing gems lead to low economic and technological efficiency in the production chain of gems and jewels. The cutting techniques can be divided into three categories as follows: (1) cabochon cutting, generally used in opaque gems, (2) faceted cutting, used in transparent gems, and (3) mixed cutting, which is a combination of the other two techniques (Mol et al., 2016; MME, 2018; Makki & Ali, 2019). The study of cutting and designer models can favor the best use of the gemstone and add value to the production chain. Characteristics such as the enhancement and utilization ratio between the weight of the raw and polished material are fundamental properties for gem valorization (Mol et al., 2016). In 2019, the Brazilian market reimported US$77,706 (commercial value) in precious and semi-precious cut stones (except diamond). The need for importing processed gemstones has been expanding since 2015, with a decrease in polishing and mineral handicraft workshops in the national market (UNCOMTRADE, 2020). Actions must be established so that this industry can develop in such a way as to expand the use of Brazilian gems in handicrafts, cutting and the manufacture of jewelry, and therefore generate employment and income in the country (Mol et al., 2016).

In the production chain of gems, a fundamental aspect is the design of the pieces. Increasingly, jewelers use the improved design to differentiate themselves, add value to the gemstone, creating a visual identity. It is considered one of the main factors for an organization's success, from product development to marketing through cost optimization, packaging, promotional material, aesthetic standards, visual identity, material adequacy, manufacturing, and ergonomics. In addition, it is an essential factor in the planning, production, and marketing strategy (MME, 2018; Milanez & Oliveira, 2013; Landim, 2010). The designer's responsibilities include being the interpreters of our desires, aspirations, and anxieties in addition to designing the components of the product itself, thereby creating a cultural identity for the product. They must understand the

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production techniques and the possibilities and obstacles of each material (Landim, 2010).

2.4 Commercialization

During the 18th century, mining society paraded adornments of colored gems set in gold and silver as a way of showcasing their fortunes and marking territory. There were no specialized craftsmen in Brazil to cut or carve stones, which kept the commercial relationship of jewels between Brazil and Portugal (Oliveira, 2019). Brazil is recognized as one of the most important countries in the international market for mineral commodities due to its large mineral reserves and quality of mines and a significant producer and exporter of high-quality minerals, making mining a vital pillar of the Brazilian economy (Alves, 2020). The country is currently the largest exporter of raw agates and amethysts. Almost 90% of extracted gemstones are exported, failing to generate employment and income in the cutting sector (MME, 2018). Data on the formal export of precious and semi-precious stones (except diamonds) for the year 2019 show US$39 million for exports of rough gems and US$305 million for exports of cut gems (UNCOMTRADE, 2020). Exporting companies have at least one designer to develop actions that contribute to the image of Brazil as a country that, in addition to raw gems, also has a jewelry industry (MME, 2018).

According to Ribeiro (2011), a decisive factor for the evolution of precious stone exports in Brazil is the choice and/or permanence of more dynamic consumer markets, with significant growth in incomes. The jewelry industry has endeavored to be transparent concerning the origin and impact on the development of the gem, considering the consumer market's demand for a responsible and ethical supply. The international community has adopted some measures to meet this requirement. However, no enforcement mechanisms systematically promote the necessary ethical practices concerning the gems trade, supply chains, and regulations. Modeling the supply chain in adopting ethical standards, responsible purchasing, and sustainability, tracing the gemstones from the mine to the market, is a significant contribution to the improvement in the gems' market value encompassing the service and manufacturing sector, thus contributing to sustainable livelihoods and local development (Makki & Ali, 2019).

2.5 Sustainable development

Sustainable development is a term widely used in many areas related to human life. The first references to the term appeared in 1972 at the UN Conference on Environment and Development. The term that was used was ecodevelopment. In 1983, the UN appointed the Prime Minister of Norway, Gro Harlem Brundtland, to chair the environmental area's commission and deepen global proposals in the commission. Then, in 1987, the Brundtland report, known as Our Common Future, appeared. The document adopted the sustainable expression development with the following definition: "how current generations meet their needs without, however, compromising the ability of future generations to meet their own needs" (Brasil, 2012). The broader definition of the term sustainable development is inserted in the 27 Principles of Sustainable Development. A document was signed at the Earth Summit, held in Rio de Janeiro, in 1992. The document recommends that new investment actions in the future are indispensable to achieve global sustainable development in the 21st century and highlights the need for cooperation in creating a sustainable economy in the mineral resource acquisition industry and the technological implementation for its use (Dubinski, 2013).

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The concept of sustainable development has been discussed (Batterham, 2017; Dubinski, 2013) since the activity is linked to nonrenewable natural resources. Thus, one of the main challenges for the sector's sustainable development consists of applying sustainability in its activities to contribute positively to the environmental, social, and economic aspects (Alves et al., 2020). Mining is one of the oldest human activities in which humanity reaches natural wealth. A key element of sustainable development in acquiring these resources is rational and economical extraction that is always concerned with the inevitable depletion of natural resources (Dubinski, 2013). Extractive industries must reduce their environmental impacts through efficient ecological management programs to contribute to sustainable development (Shen et al., 2015).

In 2014, the Brazilian Mining Institute (IBRAM), together with the United Nations Development Program (UNDP), the Brazilian government, and supporters promoted the first global dialogue on the extractive activity of mineral resources. Afterward, the country joined the proposed UN 2030 agenda for sustainable development and sustainable development objectives (SDGs). As a result of further negotiations, a mapping of mining-related impacts on the SDGs started, and the "Atlas" (mapping sustainable development objectives in mining) was developed in partnership with the World Economic Forum, Columbia University, and the Solutions Network for Sustainable Development, supported by the German International Cooperation Agency (CNI, 2017). The Atlas maps the link between mining and the SDGs, based on good practices and sustainable development that might promote actions that eradicate poverty, reduce social inequality, protect the environment, environment and climate, and guarantee a future global society based on sustainability principles (IBRAM, 2016).

The Department of Sustainable Development in Mining (DDSM) works in coordination with other sectors of the Ministry of Mines and Energy (MME) to formulate and articulate proposals for public policies, plans, and programs for the sustainable development of mining. The department bases its actions on the external demands of society, government policies, participation in environmental policy forums, the preparation of studies and projects, and training and development actions (MME, 2018). As the scope of the efforts, mineral extension Projects for Small-Scale Mining (MPE) were developed (Table 3). It is noted that these projects have a primary objective to build a relationship between sustainable development and the activity of mineral extraction, which is a challenge.

Table 3
Projects on mineral extension, year of approval, and objectives
(MME, 2018)

Project	Year of approval	Objective
National Mineral Extension Program	2008	To minimize the informality of mining and the negative impacts on the community and the environment, enabling producers for sustainable development
Small Mineral Producer Support Portal (PORMIN)	2008	To offer remote training for MPE and information relevant to the mineral segment
Mineral Telecenters	2007	To warrant physical means to the PORMIN and other websites
National Program for the Formalization of Mineral Production (PRONAFOR)	2005	Support the formalization of small-scale mineral production and elaborate on diagnoses on the obstacles to this formalization
National Seminars on Mineral Cooperatives	2005	To discuss aspects related to the organization of cooperatives and other forms of associations and public policies aimed at the sustainable development of small and medium-sized mining
Agenda 21 Mineral Program	2004	Plan, in agreement with public authorities and society, economic alternatives that can guarantee the maintenance of socio-economic levels of the municipalities in the period after the deactivation of mineral activities

Source: MME (2018)

Solving environmental challenges is vital for the activity of mineral extraction and constitutes a pillar for sustainable development. It is necessary to develop technologies to extract mineral resources that eliminate or minimize the negative effects of the activity and restore the soil for later use. Another critical factor in the sustainable development of mineral resources extraction is social responsibility, first of all in terms of the health and safety of workers, considering that the activity is characterized by a high level of risk of accidents at work (Dubinski, 2013). Arango-Aramburo et al. (2017) discuss the relationship between technology and socio-environmental performance in the mining process and argue that new technologies can increase efficiency. It also improves the process, reducing production costs and decreasing pollution and depletion of natural resources. Another possible contribution is developing preventive solutions to avoid environmental impacts and reduce the cost of corrective actions (Milanez & Oliveira, 2013). The regional economy is more vulnerable to fluctuations in commodity prices, and adverse effects of expansion and contraction cycles may occur in regions with high economic dependence on mineral extraction. This aspect is considered critical in areas with geographically remote resources, which have less opportunity for economic diversity (Mancine & Sala, 2018).

3. Methodology

The AHP is a tool for dealing with decisions under uncertainty, in which subjective judgment is quantified logically and used as a basis for decision making. In the AHP, performance ratings and attribute weights result from a series of peer comparison judgments at the same hierarchy level, assigned a discrete scale from 1 to 9 (Taha, 2008, Bui et al., 2017). This methodology uses a pairwise comparison system based on rankings (Table 4, Saaty, 1977).

Table 4
Discrete scale of pairwise comparison weights

Scale	**Degree of importance**
1	Equal importance
3	Moderate importance
5	High importance
7	Very high importance
9	Extreme importance
2,4,6,8	Intermediate values

Source: Saaty & Shang (2011)

Determination of the relative weights to classify the decision alternatives is the crucial point for applying the AHP. Considering that one deals with n criteria in a given hierarchy, the procedure establishes a matrix A= [aij] with i varying from 1 to n and j varying from 1 to n, which quantifies the decision-maker concerning the relative importance of different criteria. The pairwise comparison is made so that the line criterion i (i = 1,2,3,4...., n) is classified concerning the other criteria (Taha, 2008).

Defining element (i,j) from matrix A as aij, the AHP uses the scale in Table 4 to measure the degree of importance pairwise. Consistency in judgment requires that aij = K imply in aji= 1/k. In addition, all elements aij of the main diagonal of matrix A must be equal to 1, representing the classification of a given criterion to itself.

The degree of inconsistency (ʎ) implies whether the judgment was coherent on the part of the decision-maker concerning the pairwise comparisons. If ʎ is smaller or equal to 0.1, then the consistency is acceptable. If ʎ is higher than 0.1, then the inconsistency is high; therefore, another judgment is needed (Taha, 2008). In the present study, the multicriterial analysis AHP is used to assess the degree of importance of the factors contributing to the productive process of gems in the sustainable development of the chain. Some steps were developed before applying the Expert Choice® software v. 11 to determine the degree of importance for data processing (Figure 1).

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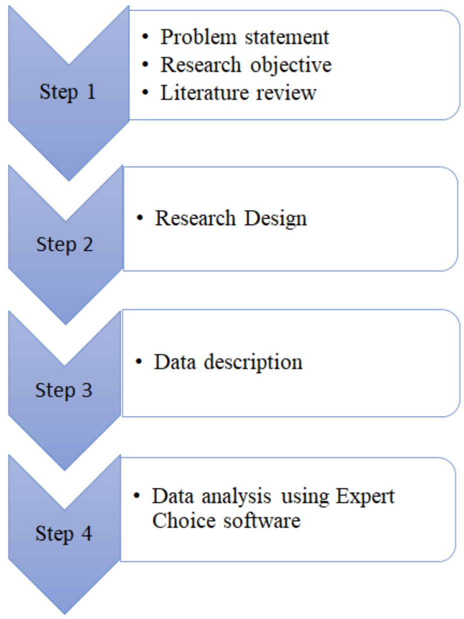

Figure 1 Research process of the analysis
Source: Adapted from Periaiah et al. (2021)

Step 1 – Explore the current situation of the gem production process in the national and international scenario, emphasizing artisanal and small production, and acquire better knowledge of the main issues related to the sustainable development of the gem production chain. Current references were used to select the factors that influence the sustainable development of the gem production chain, related by the stages of the small-scale production process, with possible effects on the chain.

Step 2 - For the construction of the hierarchy, the chosen factors were considered the sub-criteria for applying the AHP, and the stages of the production process, mining, cutting, and marketing criteria were considered (Figure 2).

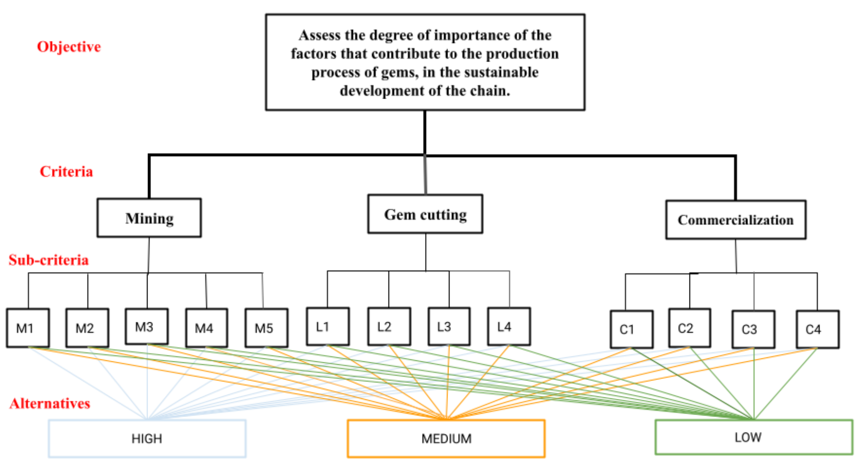

Figure 2 Elements of the multicriteria analysis (AHP) used in the present study

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Step 3 - After selecting the factors, we interpreted the interrelations of the factors and the social, economic, and environmental dimensions, the description of the factors, and the production stages, according to Table 5, to build the hierarchy of the factors the AHP process. Table 6 indicates the way the interrelations were understood.

Table 5
Description of the factors that influence the sustainable development of the gem production chain, related by the process stages in coherence with the corresponding scope and references

Steps	**Factors**	**Description of the factors**	**Scope**	**Reference**
Mining	M1-Waste reuse	Adopt measures to recycle waste, promote the transformation of waste, control the deposition of waste. Take steps to mitigate environmental impacts and improve mining processing methods.	Environmental /Economic	-Mulinari (2011); -Costa & Jornada (2015); -Matinde (2018); -Alves et al. (2020).
	M2- Health and safety of workers and the community around the mine	Promote awareness for workers about job safety and the environment and risks of mining activity. Supervise technical issues of workplace safety and worker health. Workplace stability and remuneration, ensuring their families adequate living conditions.	Social/ Environmental	-Carvalho (201)7; -Alves et al. (2020); -Bui et al. (2017); -Mancini & Sala (2018); -Dubinski (2013); -Gomes et al. (2014).
	M3- Degree of formality of the process	Control the official number of gem extractions and exports so that the informal sector does not prosper for the production and sale. Monitoring of financial compensation for mineral exploration (CFEM) is reflected in benefits for the municipality. Issuance of formal property titles that bind the miner to the land controls the miner's evasion. Greater visibility of the sector for the elaboration and implementation of public policies. Compensation for occupational issues.	Social/ Economic/Environmental	-Barreto & Bittar (2010); -MME (2018); -Milanez &Puppim de Oliveira (2013); -Bui et al. (2017).
	M4- Mine life	Measures must be taken to preserve the mine's useful life and maintain savings after depletion. Investments applied for mine rehabilitation and closure. The assessment and management of the uncertainties and risks associated with the development of mineral resources.	Environmental/ Economic	-Alves et al. (2020); -Bui et al. (2017); -Dubinski (2013).
	M5-Mine productivit	If there is control of the annual quantity of the stone explored in kilograms.	Economic/ Environmental	-Dubinski, 2013. -Cartier (2019)
Gem cutting	L1-Design	Respect and appreciate local culture, strengthen local resources, and promote the local economy.	Social/ Economic	-Canaan (2013); -Costa & Jornada (2015); -MME (2018); -Ribeiro (2011); -Milanez & Puppim de Oliveira(2013.

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	L2- Inovation	Innovation in the gem transformation process, valuing the gem's natural characteristics (color, purity, weight) and those artificially developed by cutting and design.	Economic	-Endl et al. (2019); -Milanez & Puppim de Oliveira (2013).
	L3- Technological training	Use of technology and training of professionals in polishing skills. Gem-cutting techniques for better use and shine of the gem.	Social/ Econômica/Environmental	-Costa & Jornada(2015; -Mol et al.(2016; -Ribeiro(2011.
	L4-Productivity	Refers to the control of the faceted amount of the stone (carats).	Economic/ Environmental	-Cartier (2019)
Commercialization	C1-Gem origin	Refers to if the gem originates from a conflict region or if the gemstone has a certification of origin.	Social/ Environmental/Economic	-Makki & Ali (2019).
	C2- Added value	Refers to different types of gems and their aesthetic qualities that influence the final price. Price is defined by demand/supply. Price is determined by the metals added to the gem.	Economic	-Costa & Jornada (2015); -Mancini & Sala (2018).
	C3- Product Marketing Mode commercialization of the product	Packaging, collection catalog, distribution channels. Metals added to the gem. Participation in fairs and events.	Social/ Economic	-Costa & Jornada (2015).
	C4-Productivity	If there is control of the annual quantity of stone sold in raw form, cut and inlaid in gold and silver.	Economic/ Social	- Kincaid & Smith (2021)

Table 6
Interpretation of the interdimensional relationships of the considered factors

Steps	Factors	Scope: Social	Scope: Economic	Scope: Environmental
Mining	M1-Waste reuse		Circular economy.	Impact on the bulky landscape tailings can damage the ecosystem.
	M2- Health and safety of workers and the community around the mine	Quality of life in the mine surroundings.		Risks and work accidents.
	M3- Degree of formality of the process	Inadequate labor practices tend to perpetuate social conflicts.	Underestimation of production.	Inadequate environmental practices.
	M4- Mine life		Economic stability.	Rational and economical extraction of natural resources.
	M5-Mine productivity		Profitability.	Land removal.
Gem cutting	L1-Design	Social Welfare.	Use of the gem.	
	L2- Innovation		Attractiveness, competitiveness, and market value.	
	L3- Technological training	Job opportunities for the local community.	Processing time and efficiency.	Use of natural resources.
	L4-Productivity		Added value.	Risks of accidents at work.

Commercialization	C1-Gem origin	Social status.	Gem's value.	Source certification.
	C2- Added value		Metals added for jewelry production.	
	C3- Product Marketing Mode commercialization of the product	High social level target audience.	Attractiveness.	Sustainable.
	C4-Productivity		Profitability.	

Step 4 - Based on the literature, the three consultants evaluated the degree of relevance and compared pairs between the criteria and sub-criteria, following the weight scale. The Expert Choice® software v.11 was used to achieve the final goal of assessing the degree of importance of the factors contributing to the gems' production process in the sustainable development of the chain. The sub-criteria and criteria weights were given from the selected consultants. One consultant was an academic specialist in quality applied in supply chains. The second was a researcher from the fields of environment and socio-economic development affairs. The third was an academic acting in the artisanal mining of opal in the region of Pedro II municipality, Piaui, Brazil. We explained the concepts we applied to standardize the knowledge on the topics (Tables 5 and 6). We emphasized the idea of evaluating the importance of the factors of the gem production process in sustainable chain development in coherence with the sustainability dimensions.

4. Results

Thirteen factors were selected and considered relevant for the sustainable development of the gemstone production process and divided into three groups according to the process stages. After selection, the factors were considered the sub-criteria and the steps the criteria. The weights of the pairwise comparisons, respecting the Saaty scale (Table 4), were established by the researchers, based on current literature, and following the analysis method proposed by the AHP. The weights attributed in the pairwise comparisons and the degree of inconsistency (ʎ) can be perceived in the matrices (Tables 7 - 23). The consultants were asked to assess the degree of relative importance between

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the criteria, sub-criteria, and the objective, and based on the respective questions (a, b and c), to form the pairwise comparison matrices:

a) How important are the phases of gem production in the sustainable development of the gem production chain? (related to Table 7).

Table 7
Reciprocal comparison matrix for criteria (ʎ = 0.08)

Criteria	Mining	Gem cutting	Comercialization
Mining	1	2.17	1.74
Gem cutting		1	1.87
Comercialization			1

b) What is the degree of importance of the sub-criteria in the gem production chain stages also focusing on mining sustainability? (related to Tables 8-10).

Table 8
Reciprocal comparison matrix for sub-criteria in the mining stage (ʎ = 0.01)

	M1	M2	M3	M4	M5
M1	1	1.38	1.35	1.75	1.13
M2		1	1.09	1.09	1.08
M3			1	1.31	1.02
M4				1	1.03
M5					1

Table 9
Reciprocal comparison matrix for sub-criteria in the gem cutting stage (ʎ = 0.00)

	L1	L2	L3	L4
L1	1	1.09	1.15	1.17
L2		1	1.22	1
L3			1	1.12
L4				1

Table 10
Reciprocal comparison matrix for sub-criteria in the commercialization stage (ʎ = 0.00)

	C1	C2	C3	C4
C1	1	1.08	1.11	1.20
C2		1	1.01	1.01
C3			1	1.22
C4				1

c) What is the degree of importance of the sub-criteria in the sustainable development of the production chain of gemstones? (related to Tables 11-23).

Table 11
Reciprocal comparison matrix for sub-criteria for the alternatives in sub-criteria M1 (ʎ = 0.02)

	High	Medium	Low
High	1	1.66	1.91
Medium		1	1.75
Low			1

Table 12
Reciprocal comparison matrix for sub-criteria for the alternatives in sub-criteria M2 (ʎ = 0.00)

	High	Medium	Low
High	1	1.23	1.68
Medium		1	1.31
Low			1

Table 13
Reciprocal comparison matrix for sub-criteria for the alternatives in sub-criteria M3 (ʎ = 0.04)

	High	Medium	Low
High	1	1.60	1.75
Medium		1	1.62
Low			1

Table 14
Reciprocal comparison matrix for sub-criteria for the alternatives in sub-criteria M4 (ʎ = 0.04)

	High	Medium	Low
High	1	1.89	2.01
Medium		1	1.90
Low			1

Table 15
Reciprocal comparison matrix for sub-criteria for the alternatives in sub-criteria M5 (ʎ = 0.04)

	High	Medium	Low
High	1	1.96	2.03
Medium		1	1.95
Low			1

Table 16
Reciprocal comparison matrix for sub-criteria for the alternatives in sub-criteria L1
(ʎ = 0.00)

	High	Medium	Low
High	1	1.24	1.62
Medium		1	1.34
Low			1

Table 17
Reciprocal comparison matrix for sub-criteria for the alternatives in sub-criteria L2
(ʎ = 0.03)

	High	Medium	Low
High	1	1.92	2.22
Medium		1	1.99
Low			1

Table 18
Reciprocal comparison matrix for sub-criteria for the alternatives in sub-criteria L3
(ʎ = 0.03)

	High	Medium	Low
High	1	1.73	2.97
Medium		1	1.88
Low			1

Table 19
Reciprocal comparison matrix for sub-criteria for the alternatives in sub-criteria L4
(ʎ = 0.00)

	High	Medium	Low
High	1	1.23	1.39
Medium		1	1.33
Low			1

Table 20
Reciprocal comparison matrix for sub-criteria for the alternatives in sub-criteria C1
(ʎ = 0.02)

	High	Medium	Low
High	1	1.8	2.15
Medium		1	1.93
Low			1

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Table 21
Reciprocal comparison matrix for sub-criteria for the alternatives in sub-criteria C2 (ʎ = 0.00)

	High	Medium	Low
High	1	1.19	1.51
Medium		1	1.23
Low			1

Table 22
Reciprocal comparison matrix for sub-criteria for the alternatives in sub-criteria C3 (ʎ = 0.00)

	High	Medium	Low
High	1	1.49	1.54
Medium		1	1.52
Low			1

Table 23
Reciprocal comparison matrix for sub-criteria for the alternatives in sub-criteria C4 (ʎ = 0.00)

	High	Medium	Low
High	1	1.24	1.41
Medium		1	1.35
Low			1

After pairwise comparisons between the items shown in Figure 1, based on the data collected during the survey, a general scenario was obtained and shown in Table 24.

Table 24
General results relating to the criteria, sub-criteria, and alternatives

Criteria	Sub-criteria	Alternatives High	Medium	Low	Global (%)	Rank
Gem mining (0.489)	M1 (0.174)	0.038	0.026	0.017	44.7	1
	M2 (0.214)	0.047	0.037	0.028		
	M3 (0.174)	0.038	0.027	0.019		
	M4 (0.237)	0.052	0.033	0.021		
	M5 (0.202)	0.044	0.028	0.018		
	Global (%)	46.1	32.1	21.8		
Gem cutting (0.299)	L1 (0.227)	0.030	0.025	0.019	32.5	2
	L2 (0.242)	0.032	0.020	0.012		
	L3 (0.274)	0.037	0.025	0.016		
	L4 (0.252)	0.034	0.029	0.023		
	Global (%)	44.2	32.8	23.0		
Gem commercialization (0.212)	C1 (0.249)	0.024	0.015	0.009	22.8	3
	C2 (0.245)	0.023	0.019	0.016		
	C3 (0.231)	0.022	0.017	0.012		
	C4 (0.275)	0.026	0.022	0.017		
	Global (%)	42.4	33.0	24.6		

The results suggest that sustainable development is highly related to gem mining (44.7%, rank 1), moderately related to gems cutting (32.5%, rank 2), and there is little relationship to gems commercialization (22.8%, rank 3), considering the criteria, sub-criteria, and alternatives.

4.1 Sustainable development of the gemstone production process

The criteria objective is to identify the degree of importance of the stages of the gemstone production process in the development of the chain. Table 24 shows this degree of significance, indicating what is relevant for the sustainable development of the gem production chain, according to the application of the AHP. It is noteworthy that mining is the most significant stage in the gemstone production chain, with a relevance of 48.9%, followed by gem cutting (29.9%) and, finally, commercialization (21.2%). This result is considered significant due to the low degree of inconsistency ($\lambda = 0.03$).

4.2 Hierarchy to analyze sustainable development in gem mining considering the sub-criteria (M, M2, M3, M4, M5).

The objective of the subcriteria is to identify the degree of importance of the factors that contribute to sustainable development in the stages of the gem production process. In this category, five relevant factors were selected in the process. The degrees of significance (Table 24) indicate its relevance for sustainable development in gem mining, according to the application of the AHP. It is noteworthy that in the mining process, the most

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important factors are the preservation of the mine's useful life (23.6%) and worker health and safety (21.4%). This result is significant considering the low degree of inconsistency (κ = 0.0107).

4.3 Hierarchy to analyze the sustainable development in gem cutting considering the sub-criteria (L1. L2, L3, L4).

In this category, four relevant factors were selected in the process. Data in Table 24 shows this degree of significance, showing what is appropriate for sustainable development in gem cutting according to the use of the AHP. In gem cutting, the factor that is the most significantly important is the technical qualification and skill of the stonecutter, with a percentage of 27.9%.

4.4 Hierarchy to analyze the sustainable development of gems commercialization considering the sub-criteria (C1. C2, C3, C4).

In this category, four relevant factors were selected in the process. The degree of significance (Table 24) indicates what is pertinent for sustainable development in the commercialization of gems when using the AHP. With a percentage of 27.5%, productivity in marketing stands out as the most critical factor, which suggests that it is a relevant aspect in the economic viability of the activity. This result is significant considering the low degree of inconsistency (κ = 0.0024) presented by the software, which implies that the level of inconsistency is acceptable.

4.5 Levels of the sub-criteria importance for the sustainable development of the production process of gems

Figure 2 shows the degree of importance of all factors considered relevant in the gemstone production process and the result obtained for the degree of importance of these factors, based on the AHP.

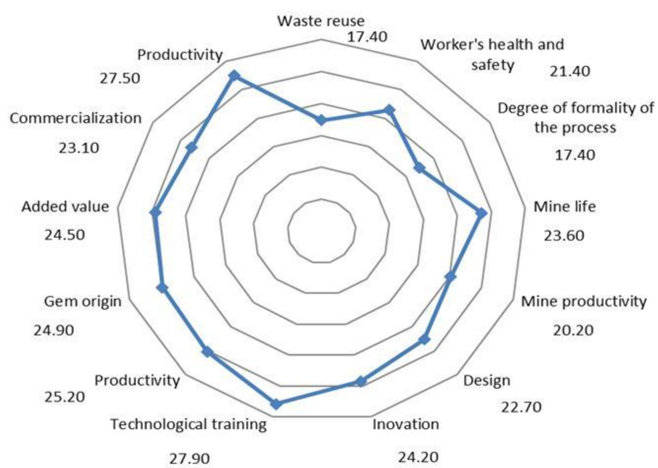

Figure 3 General view of the subcriteria adopted

Figure 3 shows the degree of importance of sustainable development based on the sub-criteria of each stage of the gemstone production process.

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5. Discussion

The mining process found that the essential factors are related to the conservation of the mine's useful life (23.6%) and worker health and safety (21.4%). Such a result corroborates the studies by Bui et al. (2017) and Dubinski (2013). This result suggests that the investment for rehabilitation and closure of a mine and the reduction in the number of fatalities at work are vital for developing any project and the public awareness that mineral resources are nonrenewable assets. Among the related factors are the percentage of productivity (20.2%), the reuse of waste, and the degree of formality of the process, with equal importance (17.4%). This result suggests that it is essential to preserve the mine's useful life, minimize waste disposal, and promote the transformation of deposited waste, in addition to issuing formal property titles, linking the miner to the land, and avoiding occupational conflicts. The results agree with Shen et al. (2015), who found that mining companies should pay adequate attention to the soft factors for adopting green (sustainable) supply chain management.

Productivity in marketing stands out as the most critical factor (27.5%), which indicates that it is a relevant factor in the activity's economic viability. According to Mancinni and Sala (2018), assessing the economic benefits involves meeting the demand for resources, which becomes relevant to subsidize the raw materials policy. The origin of the gem has a percentage of 24.9%. According to Makki and Ali (2019), the gem's origin is an economic and image-building product factor in post-conflict regions. In addition, the added value presented a percentage of 24.5%, and the form of commercialization represented 23%.

The stonecutter's technical qualification and skill in gem cutting appears to be the most significant factor (27.9%). In the study by Costa e Jornada (2015), this result is well highlighted as an essential factor for adding value to the gem, which goes far beyond the definition of shapes and quality. It is also a source of competitive advantage and performance improvement in the processing industry. The related factors are productivity (25.2%), innovation (24.2%), and design (22.7%).

The technological qualification and skills of gem-cutting are critical factors in the jewelry production process. Productivity follows in the commercialization stage and the preservation of the mine’s valuable life. The technological capacity and skill of the lapidary are essential for adding value to production and are a crucial issue for the quality of manufacture in each of the stages of the production process. This logic is valid for gem-cutting and the commercialization process, which is seen as productivity. In the mining process, the preservation of the mine's use life stands out, a result that confirms the study by Costa e Jornada (2015). All factors considered in the present study had a considerable level of relevance since the percentages of importance ranged between a maximum of 27.9% and a minimum of 17.4%.

Although, in general, our results indicate that the social benefits' importance was related to the worker's health. These findings partially agree with Carvalho (2017), who points out that a pivotal aspect of mining success is meeting the community's social goals, related to their approval to mining in their region. The corporate responsibility of mining enterprises has also grown to share the prosperity from mining with regional areas, which it possible through investing in infrastructure. Therefore, we believe the future for gem mining depends on adhering to good mining practices to protect the environment everywhere, taking social responsibility in the region's development, and promoting the community's quality of life. In relation to the social challenges, in the last decade the mining industries have been adopting the diversity and inclusion of the workforce as a strategy to increase efficiency, innovation and align the activity with the Sustainable Development Goals (SDGs). The most significant barrier to such a measure is an executive leadership and the lack of information on diversity and inclusion in international contexts in the commodity industry. While there is some progress, structural barriers still impact the adoption of diversity and inclusion in gem mining. Encouraging the establishment of social networks, recruiting employees through business groups, and instituting hiring targets are measures used by industries to increase diversity and inclusion in the workforce. This adoption is seen positively by consumers and employees, increasing revenue, shared value, and participation in the national and international market (Kincaid & Smith, 2021).

Artisanal mining almost always takes place in remote areas. Far from government regulations, it involves the circulation of money and valuable minerals, which often attract criminal behavior and negative social impacts, adversely affecting the activity. However, positive aspects can be highlighted as they can contribute to regional development and change public policies to reduce conflicts and maximize positive factors (Laing & Moonsammy, 2021). A limitation of the present study is that it comprises the knowledge of the opal artisanal mining process in a determined region of Brazil. We believe that it represents most artisanal gems mining in the country well. We also suggest that future studies expand the social, environmental, and economic dimensions following the 2030 UN agenda.

6. Conclusions

This research aimed to estimate the main factors contributing to the sustainable development of the production chain of gems, evaluating the weights in the steps of mining, cutting, and marketing of gems, using a multicriteria decision model by applying the Analytic Hierarchy Process. These factors were categorized into 13 subcriteria in the three criteria presented. From the results, it was possible to infer that mining activity was the most important criterion in the sustainable development of the chain, directly affecting the community’s development. However, we need to consider the negative impacts that influence the environmental and social environment. The challenge for the sector is balancing the positive socio-economic issues, and the harmful environmental issues to maximize the overall benefit of mining activity.

The lapidary technological skills were the most critical subcriteria in sustainable gemstone chain development. They can contribute to employment and income, improve lapidary technical skills, and add value to the gem. The research showed in the alternatives that, in general, sustainable development in the gems production chain is considered high given the related factors. In addition, we believe that assessing the positive aspects and the sector's contribution to sustainable development, considering local and global scales, is challenging.

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