

Article

Holistic Pre-Feasibility Study of Comminution Routes for a Brazilian Itabirite Ore

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Abstract: Comminution is an essential step in processing itabirite ores, given the need to liberate silica and other contaminants from the iron minerals for downstream concentration and then pellet feed production. In general, these ores in Brazil are not particularly hard to crush and grind, but both capital (CAPEX) and operating (OPEX) expenditures in this stage of preparation can be critical for the project, in particular due to uncertainties in iron ore prices. Several circuits have been designed and are in operation for this type of ore in Brazil; however, it is not yet clear which technologies are more cost-effective and in which configuration they should be applied. This work critically analyzes four comminution circuits for an undisclosed case study. For these circuits, CAPEX, OPEX, and some environmental sustainability indices, as well as qualitative technical criteria, were used in the comparisons. This work concludes that two of these process routes, especially those based on more energy-efficient technologies (and one of these still rarely explored even at bench-scale), have demonstrated to be very attractive from multiple standpoints.

Keywords: iron ore; comminution; mineral processing; techno-economic analysis; life cycle assessment (LCA); eco-efficiency; sustainable process design; process simulation; itabirite



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1. Introduction

Mining is an important industry sector that demands huge amounts of energy in its operations, particularly in comminution stages, where electrical energy use may represent about 1–2% of global energy consumption [1–3]. This issue becomes particularly critical for the mineral sector in terms of operating costs and potential environmental impacts associated to greenhouse gas (GHG) emissions. Mining operations also contribute directly and indirectly to more than 45% of global GDP [4]. However, in a scenario of global economic slowdown, the economic feasibility of new mining projects may become a challenge. Despite recent global economic crises, mining projects prevail given the need for resource-rich countries to export mineral goods, which are essential for manufacturing consumer goods globally.

Brazil is the second-largest producer of iron ore globally [5,6]; as such, iron ore mining projects play a prominent role in the national economy. Different iron ore contents are found in Brazilian deposits, being divided into two categories: high-grade iron ores (about 60% Fe content) or hematite ores, which prevail in the States of Pará and Minas Gerais, and the itabirite or “low-grade” iron ores (50% Fe content or less), which are predominant in the State of Minas Gerais.

A trend that is particularly well defined for Brazilian iron ores, except for the Carajás deposits in the north of the country, is the drop in iron grades of Run-of-Mine (RoM) ores. In the case of itabirite ores, it implies an increased complexity in ore processing due to the

need for additional beneficiation stages in order to produce a saleable concentrate (pellet feed) [5]. Furthermore, a larger amount of mine tailings is generated when compared to hematite ores, demanding an even more rigorous control and monitoring of tailings disposal. Unfortunately, tailings disposal in dams involves risks, and these have become evident in Brazil in the last decade from the tailing dam failures at two iron ore mines near the municipalities of Mariana and Brumadinho [7,8], both located in Minas Gerais.

Therefore, multiple factors have imposed challenges to present and future operations that rely on the lower grade iron ores (itabirite) from the Brazilian southeast. These include the socio-environmental impacts of mining activities and the risk of recurrence of such disasters in the region [7], the legitimate societal concern and disapproval (i.e., lack of social license to operate—SLO) in response to the recent dam rupture events, and flaws in Brazilian legislation (see, for instance [7,8]), alongside the high volatility of the iron ore price in the market from late 2004 onwards [6].

In this context, the present work aims to support the development of more sustainable iron ore mining projects in Brazil through holistic process flowsheet design. This study performs a pre-feasibility assessment of four processing routes for itabirite ores employing different technologies, with emphasis on the stages of comminution and classification. It is based on bench- and pilot-scale testing, process simulation, eco-efficiency indicators (CAPEx, OPEx, NPV, energy use, GHG emissions), and qualitative technical criteria. This work demonstrates that it is not only desirable but also feasible to integrate environmental sustainability aspects with the economic indicators commonly used in circuit design as early as in a pre-feasibility stage. The application of such an approach is still at an early stage of development in the industry in general and seems promising for a resource-intensive sector, such as the minerals industry [9,10].

2. Materials and Methods

2.1. Case Study Scoping

The present work is based on a typical itabirite ore from the Iron Quadrangle region in Minas Gerais, Brazil (Figure 1), meant to produce a concentrate for pellet feed production, with a head grade of, approximately, 43% Fe. The sample used in testing corresponded to the 80th percentile of the deposit regarding crushability and grindability. The circuit that was originally designed for processing around 20 million tons per year and that is currently in operation was based on the so-called “conventional route” for this type of ore. A conventional circuit consists of four stages of crushing, followed by two stages of ball milling with classification, and then desliming and reverse flotation. This original design was later optimized on the basis of computer simulation [11] and used as the base case in the present work (Route #1).

This work is restricted to the analysis of the stages of size reduction (mainly crushing and grinding) and classification, aiming to reach a product that is appropriate for feeding a downstream flotation stage, which is the commonly used concentration method for this ore type [5,12]. As such, it is considered that the particle size for liberation is 150 μm [13,14], and it is recommended that at least 95% of the product is below this size. A critical issue related to the processing of itabirites is controlling the production of ultrafine material (<10 μm), given its detrimental effect on the subsequent desliming and flotation stages.

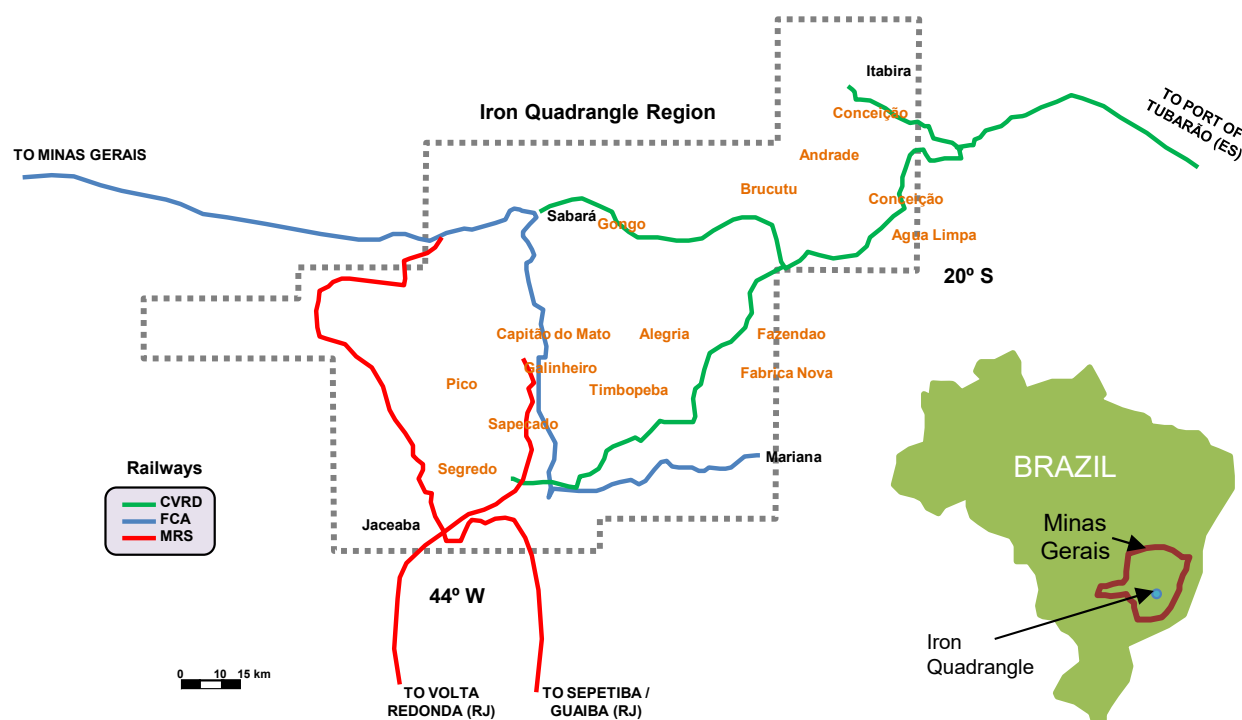


Figure 1. Map of the Iron Quadrangle region (Minas Gerais, Brazil). Adapted from [15].

2.2. Ore Properties and Design Criteria

The main characteristics of the ore in question and some design criteria are summarized in Table 1. Accordingly, the ore can be classified as low abrasiveness and low resistance to breakage.

Table 1. Summary of design criteria and selected ore properties. Adapted from: [11].

Parameter	Value
RoM feedrate [t/h]	3235
RoM moisture content [%]	<3
RoM specific gravity	3.81
RoM bulk density [kg/cm ³]	2.25
Bond abrasion index— A_i [g]	0.081
Crusher (impact) work index [kWh/t]	5.4
Bond ball mill work index [kWh/t]	8.0
JK DWT parameter— $A \times b$	$63.1 \times 2.26 = 142.6$
JK parameter— t_a	2.56
P95 in the product—feed to flotation [mm]	0.150

The ore in question is exploited in opencast mining. The product from primary crushing, common to all routes, is characterized by a size distribution with a top size of 200 mm and a large proportion of fine material (55% below 1 mm and 38% below 0.150 mm). The operational yield adopted for primary crushing was 60%, resulting in a nominal capacity of 4583 t/h. This stage of size reduction is common to all routes studied. The operational yield for all subsequent stages of crushing and grinding was 85%, which is equivalent to a nominal capacity of 3235 t/h. These criteria were used to design the base case circuit (Route #1), as well as the alternative circuits (Figure 2) [11,16]:

- Route #1: Conventional four-stage (primary + three stages) crushing, followed by two stages of ball milling;
- Route #2: One-stage cone crushing, followed by high-pressure grinding rolls (HPGR) and ball milling (BM);

- Route #3: Semi-autogenous grinding (SAG), followed by ball milling (SAB);
- Route #4: One-stage cone crushing, followed by grinding in a vertical roller mill (VRM).

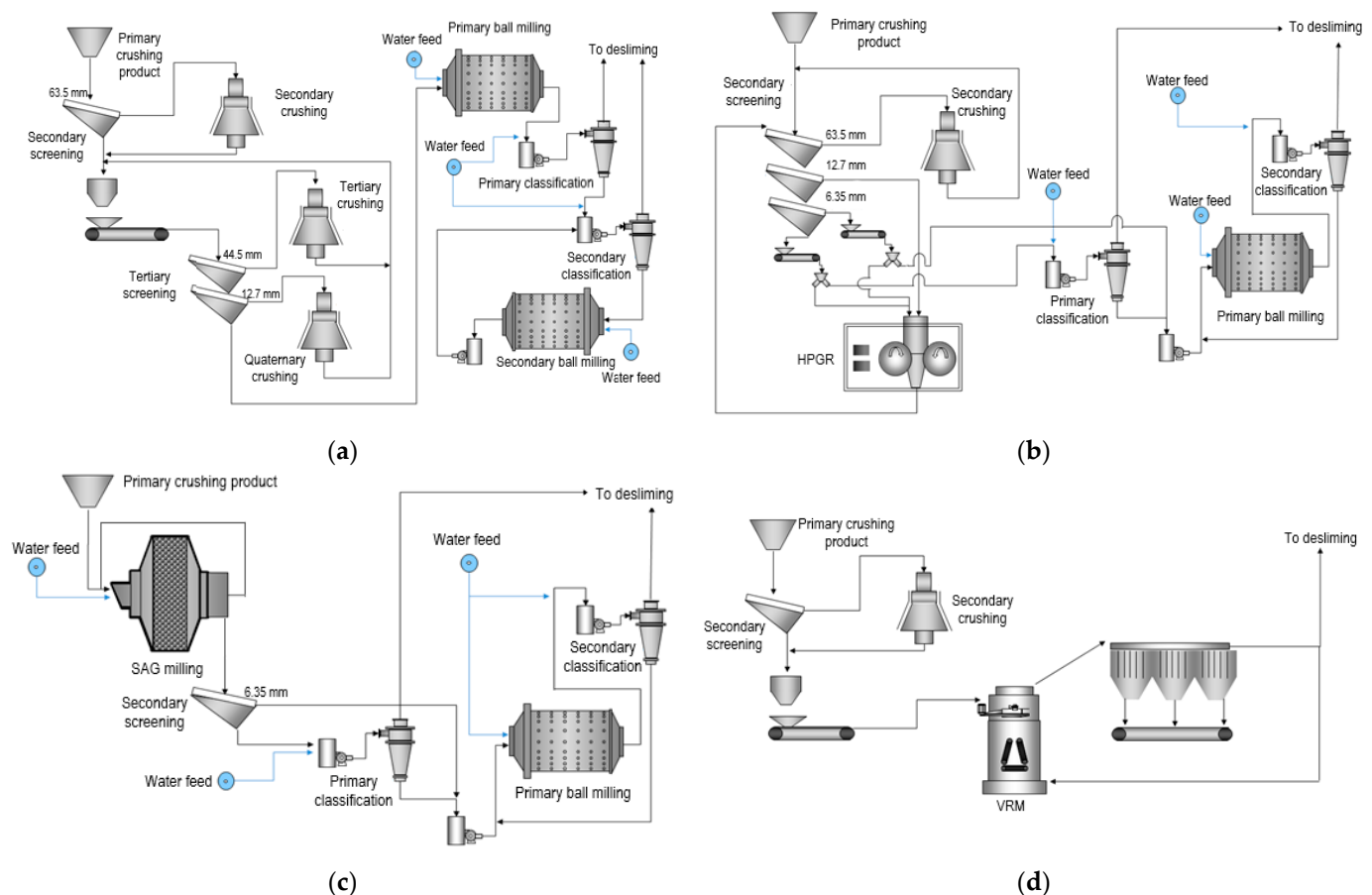


Figure 2. Comminution routes for the low-grade iron ore used as basis for comparison. Adapted from [11,16]. (a) Route #1; (b) Route #2; (c) Route #3; (d) Route #4.

Route #2 considers particular care in preparation of feed to the HPGR, which receives the -63.5 mm material from secondary crushing, although material in the size ranges 12.7 – 6.35 mm and -6.35 mm is split between the HPGR and ball milling to prevent feeding the HPGR with an exceedingly fine material. Route #3 follows the traditional SAB circuit, i.e., SAG and ball milling. Despite other routes, including single-stage SAG milling or autogenous milling demonstrated potential benefits [12], the SAB route was selected owing to its robustness to variations in both RoM size distribution and grindability. Route #4 assumes operation of the VRM with a built-in air classifier.

2.3. Sizing, Modeling, and Simulation

Screens were sized based on Karra's methodology [17], and the results were used to simulate the screens in the JKSImMet[®] software (version 5.2, JKTech, Brisbane, QLD, Australia) using the efficiency curve model [18]. This was an iterative procedure, since Karra's method is based on feed conditions, which vary due to recycle streams. Particle size distributions and mass flow rates were initially calculated with the Karra method in open circuit configuration; subsequently, efficiency curve model parameters were fitted to the calculated data and used to simulate the closed circuit in JKSImMet[®] [18]. Simulated results were then used as the input to resize the screens. The procedure was repeated until convergence between the calculated and simulated data (flow rates and size distributions) from screens was achieved. Cone crushers were sized based on technical specifications of an equipment manufacturer [11,16] and simulated in JKSImMet[®], employing the Whiten

crusher model [18]. The nominal throughput of crushers was corrected considering factors that account for the properties of the ore studied (bulk density, work index, feed size, feed moisture). The calculated number of equipment needed was oversized by 20%. Machine operation parameters were adapted from a similar project for secondary crushers, while default parameters from the simulator for tertiary and quaternary crushers were employed due to the lack of experimental data. Ore parameters for crushers were estimated from JK Drop Weight Tests (DWT). HPGRs were sized and scaled-up based on the HPGR model available in JKSimMet® [19], whose calibration relied on information gathered from pilot-scale tests carried out by Alves [20]. The HPGR was scaled up using the industrial HPGR dimensions designed for another Brazilian itabirite ore as a reference [21]. Given the limitations in predicting the throughput of the HPGR in JKSimMet®, the scale up was based on the specific throughput. This parameter mainly depends on the ore characteristics and the surface of the rolls and is usually assumed to be constant [22,23]. Therefore, the equipment throughput depends on the dimensions and speed of the rolls, the latter being the only condition to be modified to reach the necessary throughput without changing the specifications of the selected industrial HPGR. On the other hand, the specific energy of the HPGR remained constant in the scale up, as recommended by Daniel [24]. The split factor of the HPGR model was adjusted to obtain a proportion of 10% of feed material comminuted in the edge zone [24], as this fraction, which is inversely proportional to the roll length, tends to be smaller in industrial equipment.

The single-particle breakage and the compressed bed breakage in HPGRs were described by the same DWT data for crushers, based on simplifications suggested by Daniel [24]. The SAG mill was sized, scaled up, and simulated in JKSimMet® [18], based on a selected test in a pilot unit (1.8 m diameter mill) with a similar itabirite ore [12,25]. This equipment was scaled up by selecting the appropriate dimensions to process the designed throughput, using the specifications of a commercially available industrial unit. As the SAG mill model in JKSimMet® is limited for ores that are highly amenable to breakage, such as itabirites [25], the maximum discharge flow rate was verified using the model proposed by Latchireddi [26]. This model allows a more reliable estimation of the mill hold-up to avoid the slurry pooling phenomenon [16]. Regarding the total SAG mill load, it is suggested to adopt a value of 25%, given that the operational conditions of the industrial mills that served as a reference for the development of the model were close to this value [27], which was also adopted in the pilot tests performed by Rodrigues [25]. Primary cyclones were modeled and simulated using the efficiency curve model, and model parameters were obtained from an industrial cyclone efficiency curve for a similar ore [13].

Ball mills and secondary cyclones were simulated using the Moly-Cop Tools® software (version 3.0, Moly-Cop, Santiago, Chile), given the unusual bimodal appearance function associated with this ore (more details can be found in Segura-Salazar [11]). The selection and breakage parameters used for the ball mill model were based on a previous study performed with this ore [28]. Dimensions for all ball mills were based on an industrial mill used for the comminution of a similar ore in the Timbopeba Plant [13]. In the absence of experimental data, the secondary cyclones were simulated with default parameters from Moly-Cop Tools® and used the same cyclone diameter as in primary cyclones. In the case of Route #4, the design relied on estimates from the equipment manufacturer Loesche® GmbH (Düsseldorf, Germany), given that there is currently no model available on a commercial simulator to adequately represent the behavior of the VRM. Those estimates were based on bench- and pilot-scale testing with the itabirite ore.

2.4. Consumables Estimation

Some assumptions based on empirical correlations were used to calculate the consumption of wear materials associated with the processing routes, in particular, liners and grinding media of comminution machines. These estimates served as a basis for determining operating costs (OPEX), indirect energy consumption, and greenhouse gas emissions associated with the production of wear materials.

Wear rates for the liners of crushers, ball mills, and SAG mills were estimated based on Bond's correlations, using wet ball mill correlation for the latter. On the other hand, the empirical correlation proposed by Guzmán and Rabanal [29] was used for estimating grinding media wear rate in ball mills. Wear rate of balls for the SAG mill was established from an average between the prediction obtained by the updated empirical correlation originally developed for ball mills [29] and the estimation obtained based on the Bond correlation for the wet ball mill, using a correction factor of 65%, as suggested by Rosario [30].

The wear rate of HPGR rolls and studs was estimated assuming a lifetime of 4000 h for the rolls, based on the work of Ribeiro et al. [31] with a similar ore and assuming a stud pattern of the rolls similar to the one used in the Los Colorados plant [32]. Additionally, it was considered that the end of the useful life for the rolls is achieved at about 25 mm wear [32], and the wear rate was calculated considering no corrosion wear, formation of an autogenous layer of material between the studs, and uniform wear on the surface of studs without premature failures. Studs were considered to be manufactured using tungsten carbide, with an average density of 15.6 t/m³ [33]. The wear rate for the VRM was based on the estimates provided by Loesche® GmbH operating with an itabirite ore.

2.5. Environmental Indicators Based on a Streamlined Life Cycle Assessment (LCA) Framework

A streamlined approach based on the LCA methodology was developed in order to estimate environmental indicators for each of the comminution routes considered (Figure 2). The proposed method (Figure 3) focuses on the operational phase of the life cycle of the mining project [34], assuming that it represents the greatest impact in the life cycle of a comminution process, on the basis of results from previous studies [35,36]. Thus, this approach corresponds to a streamlined, gate-to-gate life cycle inventory (LCI). The methodology aims to deal with a very limited amount of information, as expected in the pre-feasibility study stage, since it refers to a processing plant that is not yet in operation. As such, only data from ore testing (bench and/or pilot-scale), alongside basic project information and design criteria for the ore under study, are available. The approach (Figure 3) consists of an initial step in which, based on the information collected, each of the potential processing routes previously established are simulated using the available data. With these results in hand and with estimates of wear rates of grinding media and liners, carbon emission factors (associated with electricity consumption and wear materials production), and specific energy consumption factors for wear materials production, it is possible to perform the simplified LCI in the selected systems. These results, in terms of inputs and outputs of the process, are normalized based on a common functional unit (e.g., with reference to the circuit feed rate), and, consequently, can be considered as performance indicators for each processing route.

For the present case, the functional unit was defined as the comminution of 3235 t/h of itabirite ore (primary crushing product) to obtain a product (preconcentrate) with 95% passing 150 µm (Table 1). Environmental and economic indicators were estimated between 2014 and 2015, relying on factors relative to that reference period. Direct energy consumption of comminution equipment, water consumption, and ultrafine material generated in each comminution route were obtained from computer simulation. For equipment other than crushers and mills (screens, pumps, conveyor belts, etc.), direct energy consumption was roughly estimated using multiplication factors for each type of circuit, based on data from plants operating with similar flowsheets but processing different ores.

Steel consumption was estimated considering only comminution equipment. Indirect energy consumption linked to the production of wear materials was calculated by multiplying the specific wear rates (g/kWh) of each component (grinding media and liners) by the corresponding simulated power (kW) in all comminution equipment. Energy consumption factors of 6.6 kWh/kg for steel [37] and 111.1 kWh/kg for tungsten carbide [38] were employed, assuming that the steel used in wear components is produced in Brazil. GHG emissions associated with direct energy consumption were estimated using an emission

factor of 0.0653 t/MWh, whose value is based on the Brazilian electricity mix for the base year of 2012 and obtained from the Ministry of Science, Technology, and Innovation database. GHG emissions associated with indirect energy consumption were estimated using emission factors of 1.54 t/t for steel [39] and 9 t/t for tungsten carbide, based on another material with a similar processing route [40]. Particulate material emissions were disregarded in this study.

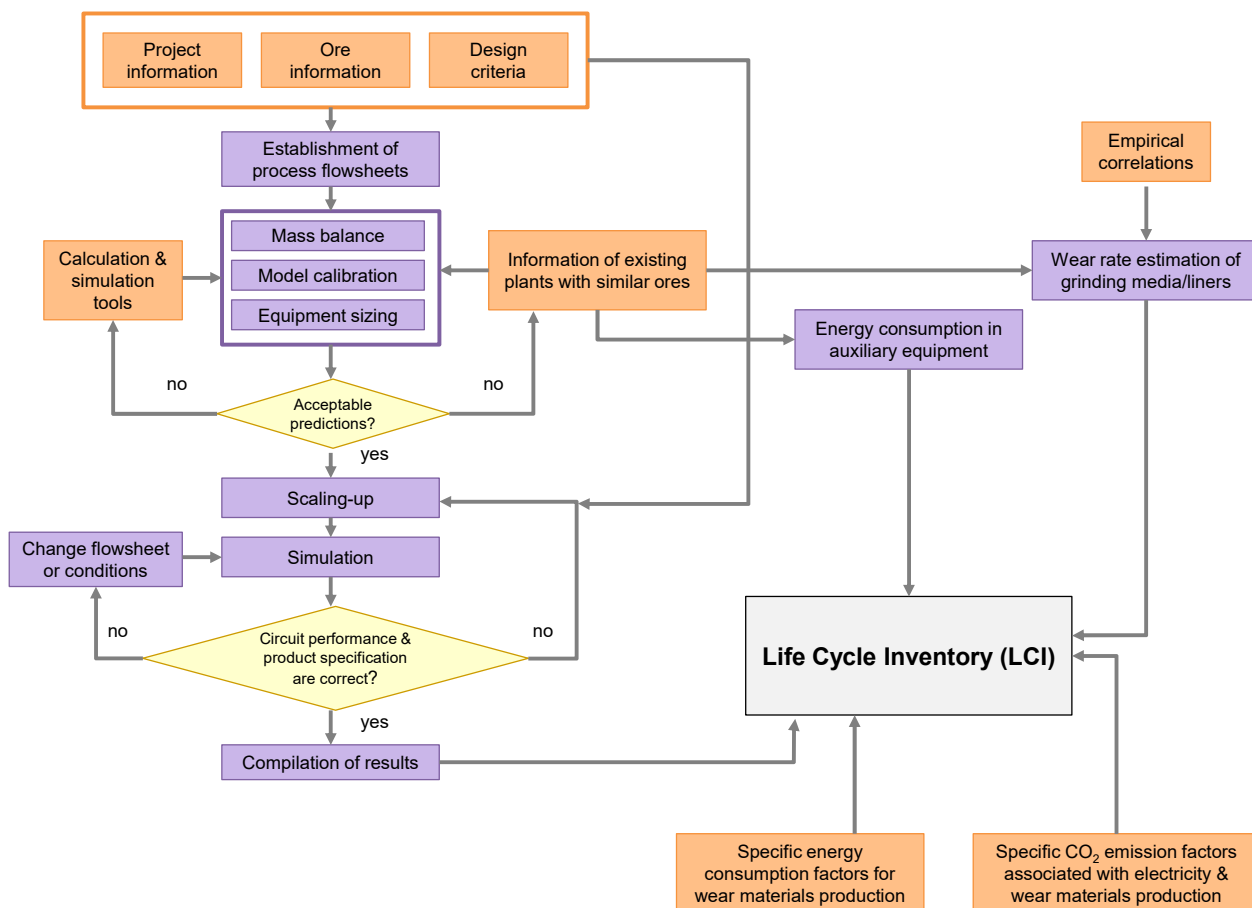


Figure 3. LCA-based approach applied to comminution processes in the design stage of a project.

2.6. Economic Indicators Based on Cost Estimation

The scope of the present work is to provide a preliminary estimate of the main costs involved in the pre-feasibility level [41], with an accuracy between -25% and $+30\%$, so that the proposed comminution routes can be compared based on capital and operating costs, using the available information.

CAPEx estimates were based on the costs of the main mechanical comminution equipment for each route and on the main costs associated, such as electromechanical assembling, industrial civil works, electrical equipment, tubing, metallic structures, and conveying; those represent at least 70% of the capital cost. The costs of some of the main equipment were provided by Metso Minerals® (Sorocaba, Brazil), and the main costs associated were based on circuit design data for projects also dealing with Brazilian itabirite ores, from factors that were established for application to the routes hereby proposed. In the case of Route #4, cost estimates were provided directly by Loesche® GmbH. It is important to emphasize that all quotations provided by equipment manufacturers were only preliminary, not being valid for negotiations or sale.

Estimates of OPEX were restricted to liners, grinding media, and energy consumption. The estimates were based on empirical equations for calculating the wear of liners and grinding media and, in some cases, on industrial data. Some of the assumptions on prices are based on the work by Rodrigues et al. [12,25]: US\$1.95/kg for grinding media, US\$0.06M for crusher liner, US\$2.3M for ball mill liner, and US\$2.6M for SAG mill liner. In the case of wear of the HPGR, an estimate of cost published by Amelunxen and Meadows [42], corresponding to US\$1.8M for each roll changeover, was used. The present work does not provide estimates of labor, automation, or administrative and general costs. The OPEX results are given in American dollars per ton of material processed (US\$/t), from a conversion of the costs of the main equipment quoted with the manufacturer on the original currency, using the average conversion rates of the corresponding month. More details concerning cost estimation can be found in Souza [16].

In order to propose the optimal selection among the different comminution routes, the total cost for each one is given through the summation of the CAPEX and the net present values of OPEX, along with the life of the project. As such, the assumptions of 20 years of operation of the plant and a minimum of 12.3% of internal rate of return were considered, which correspond to values used in a recent Brazilian project for an itabirite ore.

3. Results and Discussion

Table 2 summarizes the main results from equipment sizing and simulation of each of the processing routes proposed for the itabirite ore in question. It also presents some estimates related to the calculation of total energy consumption and GHG emissions. Table 3 presents the main contributors for the capital cost (CAPEX) and operating cost (OPEX), as well as estimates of the net present value (NPV).

Table 2. Key parameters estimated for each of the comminution routes.

Type and Quantity of Equipment		Power per Unit [kW]		Specific Energy [kWh/t]	Relative Energy Savings [%]		Relative GHG Savings [%] ²
		Nominal	Simulated		Crushing and Grinding	Total ¹	
Route #1 (Base Case)							
2nd Cone crusher—HP 400	1	315	147	0.23	-	-	-
3rd Cone crusher—HP 400	2	315	186	0.41			
4th Cone crusher—HP 800	3	600	198	0.49			
2nd Screen (single deck)—10' × 24'	2	-	-	-			
3rd Screen (double deck)—10' × 24'	6	-	-	-			
1st Ball mill—16' × 25'	1	2800	2614	0.81	(base)	(base)	(base)
2nd Ball mill—16' × 25'	2	2800	2624	3.08			
1st Classification cyclones—26"	11	-	-	-			
2nd Classification cyclones—26"	12	-	-	-			
Route #2 (HPGR-Ball milling)							
2nd Cone crusher—HP 800	2	600	124	0.16	21.4	21.0	23.4
2nd Screen (triple deck)—10' × 24'	6	-	-	-			
HPGR—2.40 m × 1.65 m	1	2 × 2400	1560	0.88			
Ball mill—16' × 25'	2	2800	2624	2.70			
1st Classification cyclones—26"	9	-	-	-			
2nd Classification cyclones—26"	32	-	-	-			
Route #3 (SAB)							
SAG mill—4.27 m × 9.75 m	1	8200	6961	2.15	−20.1	−3.2	−10.6
2nd screen (single deck)—10' × 24'	2	-	-	-			
Ball mill—16' × 25'	2	2800	1908	2.30			
1st Classifying cyclones—26"	7	-	-	-			
2nd Classifying cyclones—26"	18	-	-	-			
Route #4 (VRM)							
2nd Cone crusher—HP 400	1	315	147	0.23	−45.8	−166 (−165)	−78.7 (−75.1)
2nd Screen (single deck)—10' × 24'	2	-	-	-			
VRM—Mill (motor shaft)				4.00			
—Classifier	-	-	-	0.55			
—Fans				6.60			
—Ancillary				0.75			

¹ Including both direct energy use (crushers, mills, conveyor belts, pumps, etc.) and indirect energy consumption (consumables).

² Considering both direct and indirect GHG emissions related to direct and indirect energy consumption, respectively.

Table 3. Main costs estimated for each processing route.

Route #	CAPEx [US\$/t]	OPEx				NPV ¹ [US\$/t]
		Grinding Media [US\$/Year]	Liners [US\$/Year]	Energy [US\$/Year]	Total [US\$/t]	
1. (Base Case)	5.3	18.6 M	8.1 M	6.3 M	1.4	−15.34
2. (HPGR + BM)	4.7	14.9 M	8.4 M	4.6 M	1.1	−13.26
3. (SAB)	4.2	19.9 M	9.8 M	6.8 M	1.5	−15.39
4. (VRM)	3.7	-	4.1 M	20.1 M	1.0	−11.18

¹ Assuming operation of the plant for 20 years and a minimum internal rate of return of 12.3%/year.

According to Amelunxen and Meadows [42], the CAPEx of comminution circuits of ores with low hardness based on HPGR was estimated to be 6.4% higher than that of a circuit using only conventional (cone) crushing for the same type of ore. As ore hardness increases, this difference in CAPEx decreases, so that for hard ores, the capital cost for a coarse comminution circuit that relies exclusively on cone crushing can be even higher than for the HPGR-based circuit. Furthermore, the authors mentioned that the CAPEx of circuits based on SAG mills is always lower than those that rely on cone crushing or HPGR.

In the present work, the CAPEx was higher for the conventional route, mainly due to the costs in the ancillaries, primarily conveyor belts, electromechanical assembly, and industrial civil works. Route #2 presented a reduction of 10% in CAPEx compared to the conventional route, which agrees with estimates by Ribeiro et al. [31] in a trade-off study on the application of roller presses (HPGR) compared to tertiary cone crushing and screening. In this study, the authors demonstrated a reduction of approximately 8% in comparison to the CAPEx. However, the CAPEx associated with Route #2 was higher than that of Route #3, mainly due to the high investment cost of the HPGR in the former and to the simplification of the circuit, which demands lower ancillary costs (assembly, civil works, conveyor belts) in the latter. The CAPEx of Route #3 was about 20% lower than Route #1 (conventional circuit), which agrees with results reported by Delboni Jr. [43], who demonstrated that, in comparison to CAPEx, the SAB alternative (SAG mill followed by ball mills) results in reductions of up to 25% in comparison to conventional crushing and grinding circuits.

Surprisingly, Route #4 presented the lowest capital cost, despite relying on equipment perceived as high cost, such as the vertical roller mill (VRM). This may be explained by the high throughput of these machines when processing itabirite iron ores, as became evident in pilot-scale studies conducted at Loesche® GmbH for ore with similar characteristics [11]. This good performance of the VRM in this particular application may be linked to two effects. On the one hand, its efficient classification system could take advantage of the large proportion of natural fines in the mill feed. On the other hand, the itabirite ore is likely to be highly amenable to compressive crushing, such as by HPGR or VRM.

Regarding the operating costs, Routes #2 and #4—where machines that rely on compressive breakage are incorporated at a large extent, particularly in the coarse and medium grinding range—present themselves as the most attractive. This is primarily associated with the lower demand for wear materials in comparison to Routes #1 and #3 (Table 3). On the other hand, the operating costs associated with the energy consumption are significantly lower for Route #2 compared to Route #4, since the latter has an important demand from ancillary equipment that is part of the VRM system, mainly fans (Table 2). It is important to emphasize that the savings related to the absence of grinding media in Route #4 (Table 3) compensate economically for this high energy consumption. Route #3 presented an OPEx that is 11% higher than that of the conventional circuit (Route #1), which confirms estimates by Rodrigues [25] and might be explained, at least in part, by the higher energy consumption demanded by the SAG mill.

In general, Route #3 may be considered the most attractive from the standpoint of CAPEx, but not OPEx. As such, the economic comparison of the different comminution routes may be more directly carried out on the basis of the total net present values (NPV),

given in Table 3. In this case, Routes #2 (HPGR + BM) and #4 (VRM) are the most attractive from a purely economic standpoint.

Comparatively analyzing the circuits in terms of environmental sustainability (Table 2), Route #2, which consists of the hybrid HPGR-ball mill circuit, appears to be the best alternative compared to the other processing routes. This route accounts for reductions of approximately 21% in the total energy consumption (including both direct and indirect energy) and 23% of GHG emissions in comparison to Route #1. This is due to the higher energy efficiency in comminution and the lower demand for wear materials, the latter requiring large amounts of energy in their manufacture [36]. Routes #3 and #4, on the other hand, did not seem advantageous from the environmental perspective; total energy consumption and GHG emissions are higher than the conventional Route #1. In the case of Route #4, those estimates are considerably high, mainly due to the substantial demand of energy from each of the components of the VRM, most remarkably the fans (underlined in Table 2). This additional energy consumption could be offset by a higher iron recovery in the final product due to efficient classification and a potential improvement owing to intergranular breakage. More studies are necessary to validate and enable the use of VRM for the comminution of itabirites on an industrial scale, aiming to reduce the consumption of energy and wear materials, alongside ensuring the stability of the process due to the variability of ore and operating conditions. Additionally, Route #4 may provide a basis for a good reduction in GHG emissions in a new plant if, alongside these technologies, renewable energy sources are also incorporated, depending on the local conditions.

Route #4 also has an additional advantage from environmental and operational standpoints; it does not require water, allowing to generate a dry product with a suitable size for downstream concentration stages. This feature could help reduce the water demand of the plant or facilitate its management and reuse in the process, mainly in the case of flotation. However, the total water savings should be properly supported by realistic empirical evidence concerning the total water balance, since addition of water is required in further conventional stages (desliming cyclones, flotation cells, regrinding mills, etc.), as well as in proper disposal of ultrafine material that is discarded from the process, aiming to avoid environmental problems, such as air contamination. In this sense, further research is also required to evaluate the implications of this potential processing route in terms of helping to reduce the overall tailings generation. The reuse of water in the mining industry is becoming a more critical topic in some regional contexts, where the shortage of this resource is likely to increase, owing to factors such as climate change [44]. On the other hand, efficient water management becomes more important as ore grades drop—as is the case in itabirite or low-grade iron ores, compared to hematite or high-grade iron ores—since the volume of ore exploited from the mineral deposit increases and, therefore, the absolute volume of slimes also tends to rise. This fact, added to climate change, could potentially intensify socio-environmental risks of tailing dam failures in future operations. Route #4 stands out as the route that requires the smallest water footprint.

Ultrafine ($-10\ \mu\text{m}$) material generated in the product (classification overflow, according to Figure 2), which is the basis for the slimes removed prior to flotation, was estimated as 18% for Route #1 and 20% for Routes #2 and #3, according to simulations. Such estimates are within the expected range of slime generation for a conventional processing route [25] and are also consistent with the results of the SAG mill pilot tests performed by Rodrigues et al. [12,25] with itabirite ores. For the HPGR-based circuit, the proportion of ultrafine material simulated is within an acceptable range for the ore under study. Indeed, the simulated result (Table 2) is in line with the operational data published by Mazzinghy et al. [45], who found that HPGR does not generate excessive ultrafine material in the Minas Rio operation. However, it is worth mentioning that those estimates are subject to uncertainty, mainly due to limitations of the comminution models for this size range and the limited information on the classification of the grinding products utilizing hydrocyclones, particularly in the case of itabirites. For the route operating with the VRM, the use of shear-free type rolls may favor the reduction in generation of ultrafine material

compared to the expected amount generated by ball mills in the conventional process route [46].

Additional factors can also influence the choice of the processing route and the type of machines used in a comminution circuit. Table 4 summarizes some technical and operational aspects that must also be considered in the selection of the most appropriate processing route for the ore in question. Familiarity with the technology is yet another criterion that is relevant in the selection of one or another processing route. As such, routes that are based on the VRM (Route #4) and, to a lesser extent, HPGR (Route #2) may be regarded as less attractive than the conventional Route #1, given the widespread use of the latter in Brazil for similar ores, for instance, the case of Samarco Mineração, besides some plants from Vale in the Vargem Grande and Itabira complexes. The conventional circuit is regarded in the Brazilian iron ore industry as a very robust alternative to potential variations in ore characteristics. Still, recent cases, such as Anglo's Minas Rio project, have demonstrated the technical feasibility of the application of HPGR technology for itabirite ore on an industrial scale.

Table 4. Qualitative indices of technical and operational issues involved in each processing route analyzed.

Criteria	Route #1 (Conventional)	Route #2 (HPGR + BM)	Route #3 (SAB)	Route #4 (VRM)
Lack of familiarity with technology in iron ore	Low	Medium	Medium	High
Complexity of the circuit	High	Medium	Medium/Low	Low
Sensitivity to moisture variation in the RoM	Low	Medium	Low	High
Sensitivity to variation in grindability in RoM	Low	Medium/Low	High	Low
Sensitivity to variation in RoM size distribution	Low	Low	High	Medium/Low
Wear of grinding media	High	Medium	High	N.A.
Demand for maintenance	High	Medium	Medium	Medium
Demand for area (construction)	High	Medium	Medium	Medium/Low
Effort involved in conversion to dry concentration	High	High	High	Low

Other aspects related to the characteristics of the RoM can affect the stability of the process. On the one hand, the moisture content of the ore can affect the performance of the HPGR if it is excessively high, which can lead to a higher wear rate of the rolls, alongside a reduction in throughput. Ribeiro et al. [31] demonstrated that a pilot-scale HPGR processing a similar itabirite iron ore can lose up to 10% of its throughput when the moisture content of the ore reaches values as high as 9%. This is expected to be even more critical in the case of Route #4, given the sensitivity of the VRM process in dealing with moist feed. The risk of dealing with high moisture may be mitigated by adding a hot gas generator, but that would significantly impact the OPEX and the CAPEX of Route #4. On the other hand, fluctuations in the breakage response of the run-of-mine ore, with hardness as low as those as the ore in question (Table 1), may impose a risk for proper operation of SAG mills in Route #3 since the availability of coarse particles to act as autogenous grinding media may vary. As such, this route requires very good coordination between the mine and the plant, including the availability of high-volume ore stockpiles, as well as bins with high tonnage to guarantee the provision of material with a reasonably constant size for the different ore typologies. These matters, added to the high operation costs and the lack of prior experience on the application of SAG milling to itabirite ores, reduce the overall attractiveness of Route #3.

Table 4 also compares the potential effort involved in conversion to dry concentration. Indeed, in spite of the success of flotation in iron ore concentration, the application of dry magnetic separation has been studied as a potential alternative for full dry concentration [47,48]. In this case, Route #4 is perfectly positioned to take up this new processing strategy, whereas all other routes studied would require drying the product before concentration, which represents a significant cost.

Finally, costs associated with labor, although not estimated, will probably vary as a function of amount of equipment and circuit footprint, likely being higher for Route #1 and lower for Route #4.

4. Conclusions

Considering the CAPEx and OPEx, routes based on HPGR and VRM technologies demonstrated to be very attractive for the beneficiation of the itabirite iron ore studied. The hybrid HPGR-ball mill route also exhibits the best environmental performance among the processing routes evaluated.

The route based on VRM technology, on the other hand, demonstrated to be particularly attractive in terms of supporting the development of a dry processing route for itabirites that potentially reduces the socio-environmental risks of such types of operations. However, the high energy demand and corresponding GHG emissions question its overall environmental benefit for the comminution of itabirites. Nevertheless, opportunities exist for environmental improvement through optimal equipment configuration [11,49], energy efficiency strategies, and the coupling of these technologies to clean energy sources.

The approach used in the present work can be useful to assist mining companies in the choice of the most appropriate comminution circuit for itabirite ores on the initial stages of the life cycle of a new mining project, aiming to reach a better balance between economic attractiveness and environmental sustainability (i.e., eco-efficiency). However, it is important to emphasize that both simulations and cost analyses were based on a representative sample, whereas a mining project must consider the inherent variability of the mineral deposit. Although this study was based on steady-state simulation, future studies could also take into account the effects of circuit dynamics on their environmental, technical, and economic performance.

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