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RESEARCH ARTICLE OPEN ACCESS

OPERATIONAL FACTORS INFLUENCING QUALITY CONTROL IN ORE MILLING: A SYSTEMATIC REVIEW

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ABSTRACT

Quality control in ball mill operations in the ore industry is crucial for ensuring the final product's quality and the equipment's efficient operation. Despite its relevance, there is a scarcity of studies on this topic. This bibliographic study, based on the PRISMA protocol, involved scientometric and qualitative bibliographic analysis. The analysis revealed that the topic is rarely addressed in the literature, resulting in a limited portfolio. The identified studies explore advanced techniques such as algorithms and mathematical modeling to optimize the grinding process and improve product quality. Research also discusses advanced control systems to ensure compliance in mill operations, leading to reduced variability in material granulometry, energy savings, and increased production. Furthermore, contributions include implementing virtual sensors to monitor cement fineness in real-time, optimizing operations, and enhancing the final product's quality. However, there is a notable lack of research focused on the particle separator, a crucial component in the grinding process. These findings provide valuable insights for the effective management and operation of ball mills in the mining industry and underscore the need for future research to address these gaps.

I. INTRODUCTION

In recent years, the world has been facing sanitary, political, and economic crises that impact businesses across all sectors, prompting companies to develop strategic plans to remain competitive [1]. In this context, industries have been affected at various levels, primarily due to the COVID-19 pandemic, the Russia-Ukraine war, and the Israel-Palestine conflict, which have disrupted the production and distribution of products and materials[2], [3].

The mineral processing industry has unique characteristics, balancing financial returns with concerns for environmental preservation and impact reduction [4]. In Brazil, the mineral processing industry has shown symbolic and consistent growth each year, with a 62% increase in revenue in 2021 compared to the previous year and an 11% increase in cement demand [5].

Among the mineral processing industries, cement manufacturing has paralleled the growth of the real estate market, driven by the rise in civil and public construction projects, making it one of the primary materials in these products [6]. Cement industries are present in all regions of Brazil, covering activities from extraction and processing of the ore to the production, packaging, and distribution of cement [7], [8].

In cement manufacturing, the comminution process is considered one of the most important in the mineral industry, as it is responsible for reducing the size of ore particles [9]. Various factors can influence this type of operation, from the raw material to be processed to the sizing parameters directly related to the process [10].

In the comminution process, one of the most critical pieces of equipment is the ball mill, which performs the final fragmentation work. Therefore, precise operational control is necessary to ensure the quality of the final product [10].

Given the importance of this equipment in the segment's outcomes, the research question arises: What is the state of the literature on ball mill operations in the context of quality control?

The objective of this research is to understand the landscape of the literature regarding operational factors influencing quality control in ore milling operations, with a particular focus on ball mills, such an important piece of equipment in cement production.

II. THEORETICAL REFERENCE

II.1 QUALITY CONTROL IN THE ORE INDUSTRY

Quality control in the industry is a set of practices and processes implemented to ensure that products and services meet established quality requirements and standards [11], [12]. Quality control in the mining industry is extremely important to ensure that extracted minerals meet established quality requirements and standards [13]. This industry deals with the exploration and processing of minerals, which are used in a wide range of sectors such as metallurgy, civil construction, the chemical industry, among others.

Thus, the quality control process begins with the extraction of minerals, during which samples are collected at different points in the mine for analysis [14]. These samples undergo laboratory tests to determine the chemical composition, physical characteristics, and properties of the minerals [15]. This information is essential for evaluating the quality of the minerals and identifying their viability for use.

Laboratory tests are also used to determine the presence and concentration of impurities in the minerals [16]. These impurities can include undesirable chemical elements, environmental contaminants, or minerals of low commercial value [17]. The identification and quantification of these impurities are important to ensure that the minerals meet the quality requirements established by customers and environmental regulations [4].

In addition to laboratory tests, techniques such as real-time analysis and automation are used to monitor and control the mineral production process [18]. Sensors and devices are installed at facilities to collect real-time data on parameters such as moisture, particle size distribution, and mineral concentration [19], [20]. This data is analyzed to identify deviations and variations, allowing for immediate adjustments to keep the mineral quality within established standards [21].

Another crucial aspect of quality control in the mining industry is the implementation of quality management systems that adhere to international standards, such as ISO 9001 [22]. These systems assist in standardizing processes, documenting activities, and continuously improving operations [23]. Adopting these standards helps companies demonstrate compliance with quality requirements and build trust with customers and stakeholders. Continuous employee training and the promotion of a quality culture within the organization are also fundamental [24]. Well-trained teams that are aware of the importance of quality control can identify potential problems and implement effective solutions, contributing to the consistency and excellence of the final products [23]. In this way, quality control becomes an integrated element at all levels of production, from extraction to the delivery of the final product to the customer.

II.2 CEMENT MANUFACTURING PROCESS

To better understand the grinding operation, it is essential to comprehend the cement production process. This operation involves several stages, starting with the extraction of raw materials and crushing, preparation of raw meal, the clinker phase where the raw materials are burned, the cement grinding operation, and finally, the packaging. Figure 1 provides a detailed illustration of this process.

Figure 1: Cement manufacturing process.
Source: [25].

Thus, the process begins with the extraction of the primary component in cement production, which is extracted from carbonate deposits through quarry blasting, where limestone is removed, transported, and classified according to the physical and chemical composition present in the raw material [26]. The extracted material has large and disproportionate dimensions, making loading and transport difficult, especially when the production unit is not in the same location or near the mining site. Therefore, a crushing process is carried out, which fragments the limestone, making it easier to handle [27].

Subsequently, the raw meal preparation stage involves mixing the limestone with other "corrective" components such as bauxite, iron ore, clay, and sand to achieve better chemical stability. Various methods can be used to determine the correct dosage of the mixture, including the percentage of clay or corrective limestone [25]. The multiple chemical analyses conducted to meet the strict control of cement production may indicate the need to add residues from the production processes of other industries, such as pozzolan or blast furnace slag, to replace the raw meal material or the fuels used for clinker burning in the kiln [14], [16].

In this context, during the preheating phase, the raw meal is transported and inserted into vertical heat cyclones, where it meets the hot gases from the kiln in the opposite direction. This preheats the raw meal, initiating the first chemical reactions necessary for clinker formation. Subsequently, the precalcination process occurs in a chamber located at the bottom of the preheating cyclones, just above the kiln, known as the precalciner. After being precalcined, the raw meal moves to the next phase, entering the rotary kiln, where it is heated by fuel in a burner that can reach temperatures of 1,450°C. The precalcined meal slides through the kiln, which is slightly inclined and rotates about three to five times per minute [4], [25].

With this, the cooling stage occurs immediately when the material exits the kiln at a high temperature and is directed to a cooler (chamber) that blows cold air from electric air blowers [27]. This results in heat exchange and the generation of hot air that is reused in the process, providing better thermal efficiency for the kiln. This completes the clinker production process, and this material is then used as the primary raw material in cement production. It must be mixed with gypsum, which functions to control the setting time, with an average addition of between 3% to 4%. However, in addition to gypsum, it may be necessary to add other materials to control the quality and cost of the product [28].

In such a way, the grinding of these materials is traditionally carried out by ball mills, though some industries use horizontal roller mills [29]. In this process, grinding occurs through the interaction of grinding bodies with the particles to be ground, driven by the rotational movement of the mill. The control parameters initially consider the reliability of raw material dosing and the rotational speed of the particle separator, as higher rotation speeds result in finer material. This is a key quality parameter for cement, as it directly relates to the concrete's strength [30]. Consequently, the ground product is stored in cement silos, ready for bulk distribution in trucks or bagged on pallets.

As discussed, the cement production process is complex, involving a series of technical parameters and critical activities with a high degree of risk, thus requiring a qualified workforce. Additionally, much of this process is automated and controlled via computer at a central operations panel, significantly reducing the risk of accidents for field operators. This is a major advantage for the plant, highlighting the importance of constant maintenance of these systems [18].

II.3 COMMINUTION PRINCIPLES AND MECHANISMS

In the mineral processing industry, comminution is the process of ore fragmentation, whether by explosives or other methods. Thus, the crushing stage is primarily used after the extraction of materials in mining areas due to the size of the minerals and the specifications and adjustments needed for transport or direct commercialization [31].

Considering that electrical energy consumption is directly linked to comminution, it is the operation responsible for the largest share of energy usage [9]. In a competitive market, the high production costs associated with increased energy consumption directly impact the final product price for customers. This remains a significant challenge for equipment manufacturers, who strive to enable energy efficiency without compromising the operational effectiveness of the equipment [32].

In the technological realm, mineral processing circuits consider that the energy required for fragmentation depends on material characteristics such as size, density, and composition [16]. Each ore presents unique characteristics, necessitating individualized study to determine the most suitable equipment. Precise adjustments of operational parameters are crucial to ensure the ball mill operates efficiently and produces a high-quality final product [19]. Therefore, it is essential that the operation and monitoring of operational parameters are conducted by trained and experienced professionals.

The relationship between energy consumption and the degree of granulometry of the product generated by the grinding process is direct [33]. Monitoring fragmentation through the particle separation process is essential to determine the comminution efficiency level and prevent unnecessary processing of raw materials.

Determining a more economical and efficient process has been a significant challenge for scientists and the mineral processing industry. Despite being the subject of long-standing research, no relevant alternatives have been generated for industrial implementation [13]. In this context, it is evident that there are no comminution equipment options efficient enough to reduce the cost of these operations. Consequently, industries often use inefficient comminution mechanisms and primitive methods. These mechanisms typically include compression, abrasion, impact, and shearing [31].

Automation enhances industrial processes' effectiveness through constant parameter control [34]. The advancement of computational tools allows for frequent diagnostics of operations and simulations that relate mathematical models to previous stages of the process. This capability enables the establishment and comparison of scenarios, facilitating the projection of future industrial installations [9].

Comminution equipment operates based on the principle of applying mechanical energy, which results in the fragmentation of materials. The shape and size characteristics of the particles represent the operational mode [31]. The primary interaction mechanisms of the equipment are compression, impact, attrition, and abrasion, as illustrated in Figure 2.

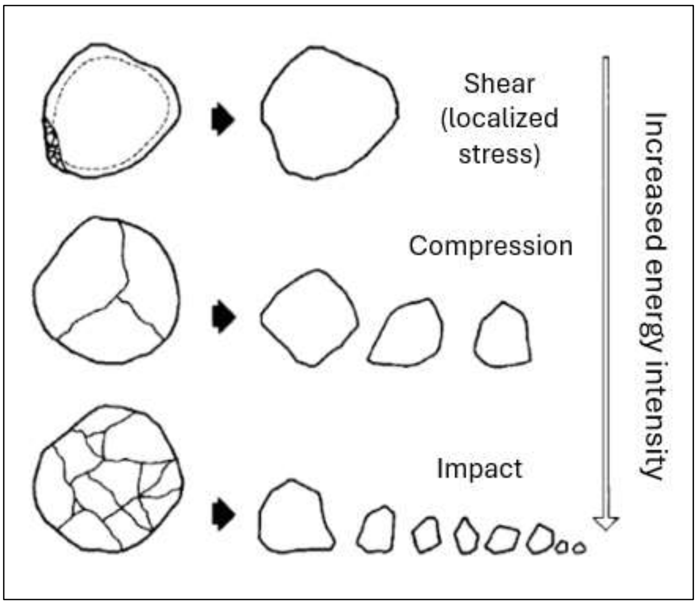

Figure 2: Fracture Mechanisms.
Source: [35].

In the compression mechanism, force is applied slowly and successively to the rock, allowing fractures to appear and subsequently break. This type of mechanism typically generates coarser and fewer fine fragments [35]. The impact mechanism utilizes rapid force applied to the particles with greater intensity than the material's strength. In this mechanism, the particles absorb more energy than necessary for fragmentation, generally producing finer material [36].

Shear comminution, while generating high energy consumption, produces a significant amount of superfine material. This mechanism is predominant in milling operations and ball mills, occurring when ore fragments move against each other, causing wear through friction [37]. Abrasion involves movement similar to friction fragmentation, differing by the particles moving in opposite directions, resulting in the production of fine material [31].

Efficient ball mill operation requires monitoring the grinding medium flow to ensure effective collisions. This avoids impact with the mill's inner lining or other grinding bodies, which results in energy loss during the process [29], [35]. Consequently, numerical simulations are necessary to address this deficiency.

II.4 CHARACTERISTICS AND MECHANISMS OF THE BALL MILL

Considered a commonly used equipment in the mineral processing industry, ball mills have a rotating cylindrical structure lined with steel or rubber plates [35]. Inside, they contain a charge of free grinding media that interact with each other due to the mill's rotational movement, facilitating particle comminution [30]. Figure 3 shows the equipment known as a ball mill.

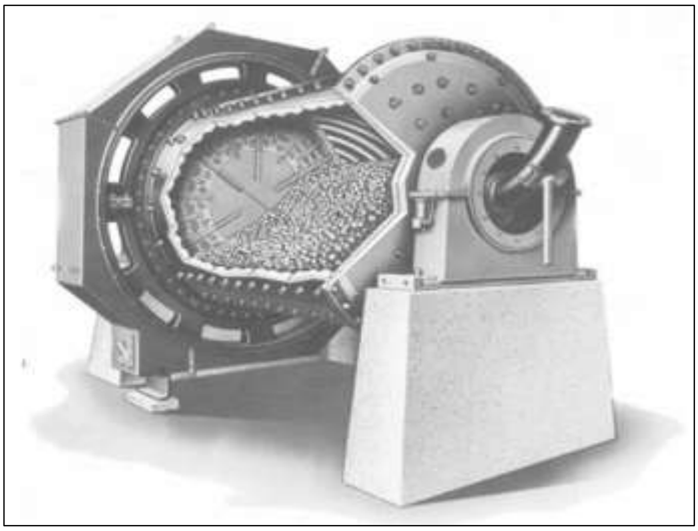

Figure 3: Ball Mill.
Source: [38].

This type of equipment is used in grinding operations involving coarser materials, as the balls have a larger contact surface, facilitating the production of fines. It should be noted that mills with a length/diameter ratio of 1.5 to 1m or smaller are not considered ball mills [39]. When they have a length greater than 3 to 5m, they are usually divided into compartments, with different ball diameters in each compartment, requiring precise sizing to define this division [40].

In the mill operation, the grinding charge can assume three movement regimes: cascading, cataracting, and centrifugation [41]. Figure 4 shows the reported types.

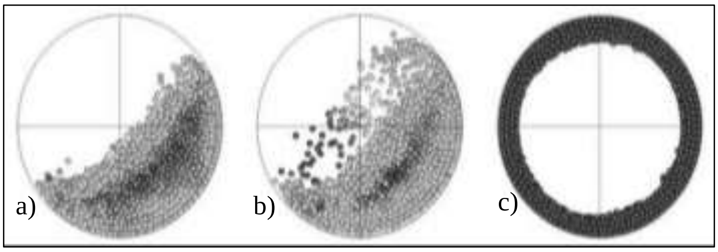

Figure 4: Operating Regimes.
a) Cascading; b) Cataracting and c) Centrifugation.
Source: [41].

The cascading regime (or cascade) is characterized by the rotational movement of the mill lifting the balls to a certain height, where they slide over each other in a cascading form due to the force of attraction [30]. This type of regime does not provide high energy generation from the impact between the bodies, and the material is broken by abrasion, making it ideal for producing a final product due to the capacity for fine production.

In the cataracting regime (or cataract), the grinding load is carried to higher elevations and detaches, falling onto the particles to be ground, causing fragmentation by impact. This is ideal for handling coarser material [42]. It is important to note that operations in this regime must be well-monitored and planned to ensure that the falling bodies land on the material to be ground and not on the mill lining. If the latter occurs, it would lead to faster wear of the lining, consequently reducing performance in terms of production [43]. Besides the mechanical operating parameters, the raw material greatly influences the yield, with factors such as moisture, porosity, initial dimensions, and shapes impacting the mill's operational efficiency [29].

Finally, the centrifugation regime occurs when the mill's rotational movement is high, causing the grinding media to be held against the walls, following the circular motion [42]. The critical speed is defined as the point where centrifugal force and gravitational force act on the particles in equilibrium, resulting in centrifugation [44].

The grinding media are indispensable components in an operating mill, responsible for performing the comminution work through interaction mechanisms. They are typically spherical, made of cast iron or steel, and come in various sizes, depending on the ore particles [45].

Determining the size of the grinding media can present a problem in some situations, considering two scenarios. In the first scenario, increasing the size of the load favors impact interaction between the particles, resulting in the breakage of larger particles [31]. The second scenario considers smaller media, increasing the contact surface area and enhancing friction interaction, thus increasing the grinding capacity. Therefore, it is recommended to define a mix of sizes among the media in the same chamber, considering the feed granulometry and the final product requirements [35].

The degree of filling is referenced according to the percentage of the mill's occupancy, which, in practice, does not exceed 50% of the mill's internal volume. This factor directly affects the grinding performance due to the motor's power, potentially damaging the equipment if the load exceeds the capacity [31].

The primary factor for the efficiency of the grinding operation is the mill's rotational speed. Literature and manufacturer manuals present varying values, making them questionable due to discrepancies when compared [30].

The mill's internal lining is crucial for operation, requiring perfect condition for optimal performance. High operational speed is a factor that can quickly wear down the lining. In the 1920s, it was common to use around 80% of the critical speed, but studies have shown that operating at about 57% of the critical speed reduces energy consumption without significantly affecting the mill's production [7].

The rotational speed determines the flow regime of the load inside the mill. Low speeds reduce the rotation number, causing the load to roll over itself, producing a cascading motion [10]. Conversely, high rotation speeds cause the load to follow parabolic trajectories, a movement known as cataracting.

The dynamic separator used in grinding operations classifies the particle size of the ground material, directing it to the end of the process or back to the beginning for reprocessing until it reaches the specified fineness [37]. The internal structure consists of a cage made of vertical bars and blades. In this type of operation, three simultaneous forces interact: the weight of the particles, the drag force of the air current, and the centrifugal force. Besides the physical aspect, there are three types of separators: first-generation, second-generation, and third-generation, all serving the same function [30].

Efficiency is achieved through the mass balance between two sub streams: the final product and the reject. When the rotational speed of the separator is high, there is an increase in both production and fines, leading to more material being rejected. Consequently, the finished product tends to decrease [46]. This occurs due to the overload factor of the mill. With the increase in the separator's rotation, the operation tends to reduce the feed to avoid overload. In other words, the production volume tends to fall with fine parameter requirements. In most scenarios, the separator retains about 20% of the material, with the remaining 80% being the finished product [30].

III. MATERIALS AND METHODS

This research can be classified as a Literature Review [47], which was based on the following steps of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) Protocol: (i) selection of Bibliographic Portfolio (BP) on quality in ball mill operations (ii) bibliometric analysis of the selected portfolio; (iii) systemic analysis of BP articles; and (iv) research question and opportunities highlighted based on the knowledge built during the process (Figure 5).

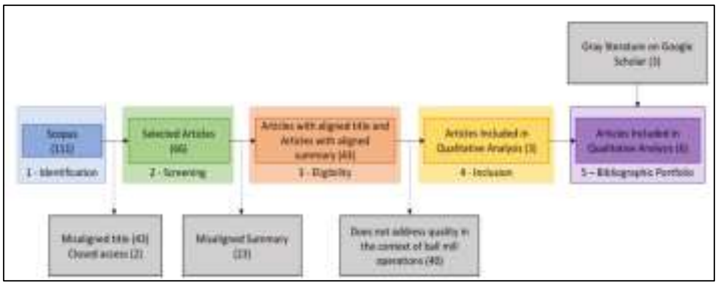

Figure 5: Article selection process based on PRISMA.
Source: Authors, (2025).

The academic database used was Scopus, employing the combination of the terms "ball mills," "quality," and "operations," with the following search string: (TITLE-ABS-KEY ("ball mills") AND TITLE-ABS-KEY (operation*) AND TITLE-ABS-KEY (quality)).

Inclusion criteria were defined as follows: only journal articles, only articles aligned with the topic, and only empirical articles. Exclusion criteria included: duplicate articles, articles not aligned with the topic, articles that do not address the impacts on quality due to operational factors in ball mill operations, and articles that do not meet the other inclusion criteria.

After the selection process, the portfolio contained only 3 aligned articles. To complement the research, the same search was conducted on Google Scholar, seeking documents aligned with this study. Only 3 aligned documents were found, resulting in a Bibliographic Portfolio of just 6 scientific documents aligned with the research, as shown in Table 1.

Table 1: Bibliographic Portfolio on Quality in Ball Mill Operations.

Authors	Source	Capes 2017-2020	Percentil
[43]	Mining Informational and Analytical Bulletin	-	49
[40]	Holos	A1	-
[48]	IEEE Transactions on Industrial Informatics	A1	98
[49]	Panduan Konseling Behavioral dengan	-	-
[50]	Powder Technology	A1	88
[29]	Federal Institute of Espírito Santo	-	-

Source: Authors, (2025).

For the bibliometric analysis, the software tools used were Mendeley, R-Studio with Bibliometrix, and VOSviewer for word clouds. The qualitative analysis was conducted based on the complete reading of the texts, highlighting their main contributions.

IV. RESULTS AND DISCUSSIONS

IV.1 SCIENTOMETRIC ANALYSIS

Quality control in ball mill operations in the mining industry is a topic that has been inadequately addressed in the literature and has shown irregular trends over the years, with significant variations. There is a noticeable gap between 2005 and 2013, during which there were no publications focused on quality control in milling operations using ball mills. After 2015, there is a higher frequency of publications involving the topic, but these are sporadic and include only specific studies. This irregularity suggests a need for greater attention and investment in research in this area to promote a more consistent and comprehensive understanding of the operational factors that influence quality in the use of ball mills.

When examining the co-occurrence of keywords, it is observed that out of 45 keywords, only 39 form a connected set. Figure 6 illustrates the co-occurrence network of keywords, showing the relationships and interactions between different terms. The red and green clusters are visually distinct, with "particle size" positioned centrally, highlighting its role in bridging the equipment-related and operation-related aspects of research. These keyword clusters help identify the core areas of research and highlight the interconnected nature of equipment characteristics and operational factors in quality control processes within ball mill operations in the mining industry.

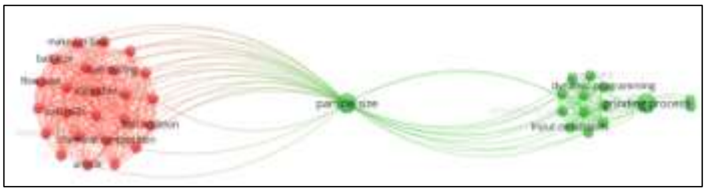

Figure 6: Keyword Clusters on Quality Control in Ball Mill Operations in the Ore Industry.
Source: Authors, (2025).

The analysis of keyword clusters in the context of quality control in ball mill operations within the mining industry reveals two main groups that are interconnected through the keyword "particle size": Ball Mill Equipment and Activities (Cluster 1 – red; Keywords: ball mills, grinding, milling, energy consumption, efficiency, operational parameters, etc.); and Operational Factors (Cluster 2 – green; Keywords: quality control, process optimization, monitoring, performance, product quality, etc.).

The Cluster 1 focuses on the ball mill equipment and the various activities involved in its operation. It is notable for having a larger number of interconnected keywords, suggesting that the characteristics and functionality of the equipment are of significant relevance in related studies. The higher density of keywords in this cluster indicates a strong emphasis on understanding and optimizing the physical and mechanical aspects of ball mills.

The Cluster 2 is concentrated on the right side of the figure and pertains to the operational factors affecting ball mill performance. It encompasses research on quality control measures, monitoring systems, and optimization techniques aimed at enhancing the efficiency and output quality of the milling process. The keywords in this cluster emphasize the importance of process management and operational adjustments in achieving optimal performance.

The keyword "particle size" serves as a crucial link between the two clusters. It is central to the discussion on quality control in ball mill operations, as it relates to both the characteristics of the equipment and the operational factors. Particle size is a key parameter in assessing the efficiency of the milling process and the quality of the final product.

One can observe a low interaction among authors and a restricted collaboration network in the research on the topic. Only two groups are connected in the same study. In this Bibliographic Portfolio, the significant number of citations attributed to the articles by [48] and [40] stands out. This observation suggests that these works have been widely recognized and referenced in the literature on the subject in question.

The relevance of these articles may lie in their contribution to advancing knowledge in the field, possibly presenting innovative approaches, robust methodologies, or impactful results. Furthermore, their influence may reflect their acceptance by the academic community and their ability to provide valuable insights that have significant implications for research and practice in the studied area.

Regarding the sources, only 3 are indexed in Scopus/Web of Science, with percentiles, and three of them are classified by Capes in the 2017-2020 quadrennium with an A1 rating.

The scientometric analysis reveals that the topic of quality control in milling operations using ball mills is still underexplored in the scientific literature. The earliest publication dates to 2005, authored by only one author. There is a significant gap until the publication by Gedraite et al. in 2014 [40]. Since then, there has been an average of one publication every two years.

This irregular behavior and the presence of gaps between publications indicate the need for greater focus and investment in research in this area, aiming to develop a deeper and more comprehensive understanding of the operational factors that impact quality in ore milling using ball mills.

IV.2 QUALITY CONTROL IN BALL MILL OPERATIONS

Quality control in ball mill operations, especially in the mining industry, is essential to ensure the quality of the final product, improve equipment operationalization, and prevent waste, environmental impacts, among other factors [20].

Upon analyzing the BP, it is noticeable that this topic, although very relevant and essential for the operations of this type of equipment, lacks associated studies. However, there is a technical deepening aimed at optimizing the equipment through the use of algorithms and mathematical modeling [48].

According to [43], the study addresses the efficiency of the milling process itself but emphasizes that as a consequence, this should increase the quality of the materials obtained. Thus, the research aims to combine two methodologies that simulate possible scenarios of the milling process in two fields of operation, and ultimately apply the combination of these methods directly to the process, with the aim of expanding the operating capacity.

The first method addresses the movement of the medium in a ball mill, for which the discrete element method (DEM) is used. However, processes in the mining industry are linked to particle movement in a fluid flow, for which the process can be modeled by computational fluid dynamics (CFD). Thus, the direction of the study is to explore the possibility of combining and applying the two DEM-CFD methods.

From Chimwani, Mulenga, and Hildebrandt's perspective [50] the distribution of ball sizes is crucial for controlling product quality and ensuring maximum production. Thus, the study's objective is to find the ball mixture that ensures compliance with this requirement. In this context, the authors developed an algorithm capable of simulating grinding circuits focused on ball wear, and this model was validated, providing relevant results for the issue. Therefore, this work has significant characteristics as it addresses the problem and approaches the topic with technical relevance, well-explained by the authors.

Following the same research line, [48], also developed a study based on algorithms and simulations, which concerns the efficiency of the ore grinding process. According to the authors, this efficiency depends on the circulating load and the particle size of the product, making these two operational points crucial for quality control in the operation. Simulations were conducted, obtaining significant results.

Considering the approach of the three studies mentioned earlier, these belong to the empirical reports extracted from Scopus, having relevance due to the recognition of the database. Thus, we observe an important point regarding the methodology model, as both studies use mathematical modeling to conduct simulations. Such observation is essential due to the positive outcome presented by the journals, contributing safely and accurately to the operation.

The three reports retrieved from Google Scholar focus on the installation of systems and hardware in computers, aiming to monitor the grinding process and improve operational practices that contribute to the operation itself, consequently presenting elevated aspects regarding quality control.

The study conducted by [49], aims to control the speed and rotation in the grinding process using a ball mill. To optimize this process, a frequency inverter controlled by Compact Field point hardware and LabVIEW software was employed. The system was studied, and a speed control application for the grinding process was developed within the programming environment. This application allows for the combination of different speeds according to the mill's load. Subsequently, tests were conducted in a laboratory setting, where the operation was managed by considering a series of factors to ensure reliable results. The results of the laboratory simulations showed that the optimization objective was satisfactorily achieved, as expected by the authors.

According to [40] developed an advanced control system that incorporates a multivariable controller coupled with a regulatory control system. The implementation of this system in a ball mill allows the operation to achieve compliance conditions, ensuring maximum efficiency and improving the final product's milling finish. As a result, the system demonstrated significant benefits, including reduced variability in the material's particle size distribution after grinding, decreased energy consumption, and increased production output.

Finally, [29] believes that providing online information about cement fineness is a significant opportunity for the cement grinding process using ball mills. This approach can optimize operations, reduce energy consumption, and enhance the quality of the final product. The study presents three types of supervised regression models for predicting cement fineness: Multilayer Perceptron Neural Network (MLP), Support Vector Machine (SVM), and Radial Basis Function Neural Network (RBFNN).

Tests were conducted on a laboratorial scale to obtain fineness data for the material entering and exiting the mill. Subsequently, a virtual sensor based on the MLP model was designed and implemented. The system was tested in a real-world setup, and despite the complexity of deploying this system, data preprocessing enabled advantageous results, providing greater accuracy in monitoring cement fineness.

Regarding the operational factors addressed in the studies, applications involving software, system automation, and mathematical modeling focused on quality control in grinding operations were evident. However, the entire Bibliographic

Portfolio lacked research directed towards the particle separator, an essential component in the grinding process responsible for classifying the size of comminuted material particles. The integrity and operation of this equipment are crucial for maintaining quality parameters in the process.

V. CONCLUSIONS

This study revealed that quality control in ball mill grinding operations is still an underexplored topic in the scientific literature, despite its industrial importance, especially in mining. Through a systematic analysis of the existing literature, it was possible to map the conducted studies, identify significant gaps, and better understand the methods and approaches used so far.

The bibliographic analysis of the portfolio revealed that the existing studies predominantly focus on strategies for controlling the fineness of the mill's output material, highlighting the importance of this parameter in ensuring the quality of the final product. These studies also emphasize benefits in terms of costs and operational efficiency. The bibliometric analysis revealed a scarcity of authors and a limited collaboration network, suggesting that the participation of larger groups could enrich and enhance ideas in this complex area. However, there is a growth trend driven by new technologies and market demands.

The studies indexed in Scopus stand out for their process simulations aimed at resource optimization and operational cost reduction, while the studies identified in the Google Scholar database focus on practical applications in a laboratorial scale. There is little intersection between these types of studies, indicating the need for greater integration between theoretical and practical approaches.

The analyzed studies do not sufficiently address the use of the particle separator, a crucial component for quality control and the proper functioning of the ball mill. Additionally, the control of the mix of ball sizes, which is essential for optimizing the grinding process, deserves more in-depth study.

This study is pioneering in bringing theoretical elements that support scientific work in the mining industry, which extensively uses ball mills. It significantly contributes to the literature by identifying new directions for future research, highlighting opportunities for both empirical and theoretical studies.

For future work, it is recommended to conduct empirical research that directly involves command centers, exploring practical applications in the industrial environment. Comparative studies between laboratory experiments and applications on real equipment would enrich discussions on the topic. Furthermore, future studies could focus on the use of particle separators and deepen the study of the ball mix to ensure quality control in the mineral grinding process using ball mills.

In this interim, it is concluded that although the topic is crucial for the industry, the literature on quality control in ball mills is limited and dispersed. This study not only fulfills the objective of mapping the current state of research but also establishes a robust starting point for future investigations, encouraging the continuity and deepening of research in this vital area.

VI. AUTHOR'S CONTRIBUTION

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Investigation: Eliana de Jesus Lopes, Guilherme Graciano dos Santos, Eng. and Adriano Ricardo Almeida Alexandre, Dr.
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VII. REFERENCES

[1] Q. Liu, X. Qu, D. Wang, J. Abbas, and R. Mubeen, "Product Market Competition and Firm Performance: Business Survival Through Innovation and Entrepreneurial Orientation Amid COVID-19 Financial Crisis," *Front. Psychol.*, vol. 12, no. 1, pp. 1–12, Mar. 2022, doi: 10.3389/fpsyg.2021.790923.

[2] Z. Cekerevac and M. Bogavac, "Impact of covid-19 and Ukraine-Russia war on the international trade and logistics," *MEST J.*, vol. 11, no. 1, pp. 19–30, Jan. 2023, doi: 10.12709/mest.11.11.01.03.

[3] H. Zhang, "The Impact of COVID-19 on the Manufacturing Industry and Solutions," *Highlights Business, Econ. Manag.*, vol. 13, no. 1, pp. 142–148, May 2023, doi: 10.54097/hbem.v13i.8637.

[4] J. J. Marquina Araujo *et al.*, "Environmental impacts in the commercialization of minerals," in *Proceedings of the 21th LACCEI International Multi-Conference for Engineering, Education and Technology (LACCEI 2023): "Leadership in Education and Innovation in Engineering in the Framework of Global Transformations: Integration and Alliances for Integra*, 2023, pp. 1–12. doi: 10.18687/LACCEI2023.1.1.254.

[5] IBRAM, "Mineração em números 2022," *IBRAM*, 2022. https://ibram.org.br/publicacoes/?txtSearch=&checkbox-section%5B%5D=1236 (accessed Apr. 16, 2024).

[6] M. D. Gala and M. M. Bhoyar, "Equity Research Analysis of Cement Industry," *MET Manag. Rev.*, vol. 08, no. 02, pp. 44–56, 2021, doi: 10.34047/MMR.2020.8206.

[7] A. C. R. da R. Souza, H. C. Gomes, and I. F. G. Guimarães, "A statistical analysis of the relationship of civil construction GDP to cement production in Brazil," *Res. Soc. Dev.*, vol. 11, no. 7, p. e27011729902, May 2022, doi: 10.33448/rsd-v11i7.29902.

[8] D. C. Reis, M. Quattrone, J. F. T. Souza, K. R. G. Punhagui, S. A. Pacca, and V. M. John, "Potential CO 2 reduction and uptake due to industrialization and efficient cement use in Brazil by 2050," *J. Ind. Ecol.*, vol. 25, no. 2, pp. 344–358, Apr. 2021, doi: 10.1111/jiec.13130.

[9] A. R. Hasankhoei, M. Maleki-Moghaddam, A. Haji-Zadeh, M. E. Barzgar, and S. Banisi, "On dry SAG mills end liners: Physical modeling, DEM-based characterization and industrial outcomes of a new design," *Miner. Eng.*, vol. 141, p. 105835, Sep. 2019, doi: 10.1016/j.mineng.2019.105835.

[10] R. de F. Oliveira, "Uma revisão dos princípios de funcionamento e métodos de dimensionamento de moinhos de bolas," Escola de Engenharia da Universidade Federal de Minas Gerais, 2012.

[11] W. I. M. da Silva, D. B. de Alencar, and J. de A. Brito Junior, "Management integration plan in a civil construction company," *ITEGAM- J. Eng. Technol. Ind. Appl.*, vol. 5, no. 20, pp. 1–10, 2019, doi: 10.5935/2447-0228.20190075.

[12] V. V. Reznikova and I. M. Kravets, "Goods quality management and control systems," *Econ. Law*, vol. 1, no. 1, pp. 3–18, May 2022, doi: 10.15407/econlaw.2022.01.003.

[13] N. Pryadko, I. Mladetsky, S. Dziuba, and K. Ternova, "Investigation of the

control characteristics of mineral processing technology indicators," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 970, no. 1, p. 012001, Jan. 2022, doi: 10.1088/1755-1315/970/1/012001.

[14] A. de Faria Junior, G. de Tomi, L. M. Sant'Agostino, and J. F. C. L. Costa, "O impacto do tipo de amostragem no controle de qualidade na lavra," *Rem Rev. Esc. Minas*, vol. 63, no. 2, pp. 385–392, Jun. 2010, doi: 10.1590/S0370-44672010000200025.

[15] H. Lieberwirth, O. Popov, T. Aleksandrova, and N. Nikolaeva, "Scientific substantiation and practical realization of selective comminution process of polymetallic mineral raw materials," *E3S Web Conf.*, vol. 192, no. 1, p. 02003, Sep. 2020, doi: 10.1051/e3sconf/202019202003.

[16] W. Xu *et al.*, "Process Mineralogy Characteristics and Flotation Application of a Refractory Collophanite from Guizhou, China," *Minerals*, vol. 11, no. 11, p. 1249, Nov. 2021, doi: 10.3390/min11111249.

[17] W. D. Judge and G. Azimi, "Recent progress in impurity removal during rare earth element processing: A review," *Hydrometallurgy*, vol. 196, no. 1, p. 105435, Sep. 2020, doi: 10.1016/j.hydromet.2020.105435.

[18] A. Massaro, "Advanced Control Systems in Industry 5.0 Enabling Process Mining," *Sensors*, vol. 22, no. 22, p. 8677, Nov. 2022, doi: 10.3390/s22228677.

[19] D. Back, D. Theisen, W. Seo, C. S.-J. Tsai, and D. B. Janes, "Development of Interdigitated Capacitive Sensor for Real-Time Monitoring of Sub-Micron and Nanoscale Particulate Matters in Personal Sampling Device for Mining Environment," *IEEE Sens. J.*, vol. 20, no. 19, pp. 11588–11597, Oct. 2020, doi: 10.1109/JSEN.2020.2995960.

[20] E. Brattich *et al.*, "How to Get the Best from Low-Cost Particulate Matter Sensors: Guidelines and Practical Recommendations," *Sensors*, vol. 20, no. 11, p. 3073, May 2020, doi: 10.3390/s20113073.

[21] A. Figiel and I. Ková, "Safety requirements for mining systems controlled in automatic mode," *Acta Montan. Slovaca*, vol. 25, no. 1, pp. 417–436, 2020, doi: 10.46544/AMS.v25i3.13.

[22] N. Singh, A. P. Singh, and A. P. Singh, "Quality management systems and ISO 9000 effectiveness: A review," *Indian J. Pharm. Pharmacol.*, vol. 7, no. 3, pp. 142–146, Oct. 2020, doi: 10.18231/j.ijpp.2020.024.

[23] "Design of Methodological Platform to Support the Integration of Standardized Quality Management Systems Applicable in the Mining Industry," *Acta Montan. Slovaca*, vol. 1, no. 27, pp. 1017–1027, Feb. 2023, doi: 10.46544/AMS.v27i4.15.

[24] E. de J. Lopes, A. B. V. de Souza, J. Í. da S. Pierre, R. A. Rêgo Júnior, and F. A. F. da Ponte, "Application of methods-time measurement as a tool to improve productivity in a beauty salon," *ITEGAM- J. Eng. Technol. Ind. Appl.*, vol. 8, no. 35, pp. 1–10, 2022, doi: 10.5935/jetia.v8i35.817.

[25] G. Visedo and M. Pecchio, *Roadmap Tecnológico do Cimento: potencial de redução das emissões de carbono da indústria do cimento brasileira até 2050*. Rio de Janeiro: SNIC, 2019. [Online]. Available: https://coprocessamento.org.br/wp-content/uploads/2019/11/Roadmap_Tecnologico_Cimento_Brasil_Book-1.pdf

[26] H. Gokcekus, N. Ghaboun, D. U. Ozsahin, and B. Uzun, "Evaluation of Cement Manufacturing Methods Using Multi Criteria Decision Analysis (MCDA)," in *2021 14th International Conference on Developments in eSystems Engineering (DeSE)*, Dec. 2021, pp. 39–43. doi: 10.1109/DeSE54285.2021.9719399.

[27] C. Tregambi *et al.*, "Solar-driven production of lime for ordinary Portland cement formulation," *Sol. Energy*, vol. 173, no. 1, pp. 759–768, Oct. 2018, doi: 10.1016/j.solener.2018.08.018.

[28] B. B. Mariani, J. da S. Andrade Neto, N. S. de Amorim Júnior, and D. V. Ribeiro, "Efeito da incorporação de resíduo de TiO2 (MNR) na formação das fases mineralógicas de clínquer Portland," *Ambient. Construído*, vol. 19, no. 1, pp. 57–71, Mar. 2019, doi: 10.1590/s1678-86212019000100293.

[29] R. Pereira, "Estimativa da finura do cimento durante o processo de moagem em moinhos de bolas," Instituto Federal do Espírito Santo, 2020. [Online]. Available:https://repositorio.ifes.edu.br/bitstream/handle/123456789/703/DISSERTAÇÃO_Estimativa_Finura_Cimento_Processo_Moagem.pdf?sequence=1&isAllowed=y

[30] X. Lu, B. Kiumarsi, T. Chai, Y. Jiang, and F. L. Lewis, "Operational Control of Mineral Grinding Processes Using Adaptive Dynamic Programming and Reference Governor," *IEEE Trans. Ind. Informatics*, vol. 15, no. 4, pp. 2210–2221, 2019, doi: 10.1109/TII.2018.2868473.

[31] P. Semsari Parapari, M. Parian, and J. Rosenkranz, "Breakage process of mineral processing comminution machines – An approach to liberation," *Adv. Powder Technol.*, vol. 31, no. 9, pp. 3669–3685, Sep. 2020, doi: 10.1016/j.apt.2020.08.005.

[32] M. Eisenlauer and U. Teipel, "Comminution energy and particulate properties of cutting and hammer-milled beech, oak, and spruce wood," *Powder Technol.*, vol. 394, no. 1, pp. 685–704, Dec. 2021, doi: 10.1016/j.powtec.2021.03.072.

[33] C. Ciobanu, P. Tudor, G.-A. Constantin, and G. Musuroi, "Determination of granulometrical composition of the clinker by grinding in a ball mill to determine the specific consumption of additional energy," *E3S Web Conf.*, vol. 180, no. 1, p. 04007, Jul. 2020, doi: 10.1051/e3sconf/202018004007.

[34] C.-J. J. L. Farrell *et al.*, "Two-step penalised logistic regression for multi-omic data with an application to cardiometabolic syndrome," *PLoS One*, vol. 11, no. 1, pp. 1150–1156, 2021, doi: 10.1016/j.jcin.2015.04.006.

[35] C. D. C. RODRIGUES, "Dimensionamento De Moinho De Bolas Utilizando O Método Do Balanço Populacional," *Eng. Minas do Dep. Eng. Minas*, pp. 1–9, 2019, doi: .1037//0033-2909.I26.1.78.

[36] W. Zhou, D. Wang, G. Ma, X. Cao, C. Hu, and W. Wu, "Discrete element modeling of particle breakage considering different fragment replacement modes," *Powder Technol.*, vol. 360, no. 1, pp. 312–323, Jan. 2020, doi: 10.1016/j.powtec.2019.10.002.

[37] T. Kundu, S. Kanta Das, S. Kumar Tripathy, and S. I. Angadi, "Performance evaluation of the VSK separator for treating mineral fines," *Miner. Eng.*, vol. 167, 2021, doi: 10.1016/j.mineng.2021.106883.

[38] Metso, *Manual de Britagem*, 6th ed. Metso Minerals, 2005.

[39] N. A. Toprak, A. H. Benzer, C. E. Karahan, and E. S. Zencirci, "Effects of grinding aid dosage on circuit performance and cement fineness," *Constr. Build. Mater.*, vol. 265, no. 1, p. 120707, Dec. 2020, doi: 10.1016/j.conbuildmat.2020.120707.

[40] R. Gedraite, S. M. da S. Neiro, A. S. Morais, L. Vieira, and L. A. Rodrigues, "Considerações práticas sobre controle avançado de processo aplicado a moinho de bolas," *HOLOS*, vol. 3, pp. 122–132, Jul. 2014, doi: 10.15628/holos.2014.1764.

[41] R. Y. Yang, A. B. Yu, L. McElroy, and J. Bao, "Numerical simulation of particle dynamics in different flow regimes in a rotating drum," *Powder Technol.*, vol. 188, no. 2, pp. 170–177, Dec. 2008, doi: 10.1016/j.powtec.2008.04.081.

[42] O. Ishnazarov, J. Mavlonov, and D. Mardonov, "Control of ball mill operation depending on ball load and ore properties," *E3S Web Conf.*, vol. 461, no. 1, p. 01091, Dec. 2023, doi: 10.1051/e3sconf/202346101091.

[43] A. S. Opalev and A. A. Palivoda, "Modeling of the liquid-solid particle systemin the coupling solution of the task in rocky dem and ansys fluent ," *Min. Informational Anal. Bull.*, no. 12–1, pp. 78–93, 2022, doi: 10.25018/0236_1493_2022_121_0_78.

[44] A. D. Bardovskiy, S. M. Gorbatyuk, A. M. Keropyan, and P. Y. Bibikov, "Assessing Parameters of the Accelerator Disk of a Centrifugal Mill Taking into Account Features of Particle Motion on the Disk Surface," *J. Frict. Wear*, vol. 39, no. 4, pp. 326–329, Jul. 2018, doi: 10.3103/S1068366618040037.

[45] C. Mayer-Laigle, R. K. Rajaonarivony, X. Rouau, and C. Fabre, "Properties of biomass powders resulting from the fine comminution of lignocellulosic feedstocks by three types of ball-mill set-up," *Open Res. Eur.*, vol. 1, 2022, doi: 10.12688/openreseurope.14017.2.

[46] Y. Liu, J. G. Song, W. L. Zhu, D. L. Zhang, H. B. Wen, and R. Huang, "Effect of Ball Milling Technology on Properties of Refractory Waste," *Key Eng. Mater.*, vol. 927, no. 1, pp. 143–148, Jul. 2022, doi: 10.4028/p-49gm95.

[47] E. de J. Lopes, M. Bouzon, and M. de C. Carneiro Neto, *Revisão Sistemática*. Sobral: CBL, 2024. [Online]. Available: https://www.researchgate.net/publication/378007404_Revisao_Sistematica

[48] X. Lu, B. Kiumarsi, T. Chai, Y. Jiang, and F. L. Lewis, "Operational Control of Mineral Grinding Processes Using Adaptive Dynamic Programming and Reference Governor," *IEEE Trans. Ind. Informatics*, vol. 15, no. 4, pp. 2210–2221,

2019, doi: 10.1109/TII.2018.2868473.

[49] D. A. ANABUKI, “Aplicação do controle de um processo de moagem em moinho de bolas através do sistema Labview-Compact Fieldpointinversor de freqüência,” Universidade Federal de Pernambuco, 2005.

[50] N. Chimwani, F. K. Mulenga, and D. Hildebrandt, “Ball size distribution for the maximum production of a narrowly-sized mill product,” *Powder Technol.*, vol. 284, pp. 12–18, Nov. 2015, doi: 10.1016/j.powtec.2015.06.037.