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TOPICAL REVIEW

Exploring the Context of Industry 4.0, Continuous Processes, and Mining Industry: A Systematic Literature Review and Research Directions

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ABSTRACT Industry 4.0 offers significant potential to enhance efficiency and competitiveness in continuous processes, such as those in the mining sector. However, the implementation of its principles in continuous production sectors presents specific challenges, mainly due to the unique characteristics of the processed materials and the demand for continuous production. This study conducted a systematic literature review to investigate the application of Industry 4.0 in continuous processes within the mining sector, focusing on the relationship between Industry 4.0 design principles and their integration into these processes. The objectives were to: (i) identify and describe existing evidence on the integration of Industry 4.0 in continuous processes in mining, (ii) synthesize the opportunities Industry 4.0 offers for continuous production processes in mining, and (iii) foster discussions on future research directions. The results highlighted critical gaps in the application of Industry 4.0 principles in the mining industry and proposed a comprehensive theoretical framework that maps opportunities and provides practical implementation guidelines. This framework emphasizes the need for customized approaches to improve operational efficiency, reduce costs, and enhance global competitiveness. The conclusions offer a foundation for future empirical research and promote innovation and digital transformation in the mining industry, focusing on adapting optimization and process control techniques for continuous processes.

INDEX TERMS Bibliometric review, continuous processes, industry 4.0, mining industry, interconnection, technical assistance, information transparency, decentralized decisions, sustainability.

I. INTRODUCTION

Industry 4.0, has been widely characterized in discrete production environments [1]. However, this new paradigm is not confined to a specific industrial sector but emanates from the evolution of traditional production models [2]. Within continuous processes, as is the case with many process industries (PI), there is a delay in the application and exploration of the advantages of innovative technologies to enhance the flexibility and productivity of their processes [3].

In a broader context, as Industry 4.0 advances across multiple sectors, its corresponding application and exploration in continuous processes, such as those in the mining industry, becomes imperative to address the inherent challenges of these complex environments. Digital transformation in these industries is essential not only for operational optimization but also for ensuring long-term competitiveness and sustainability [4].

Various studies have conducted a comprehensive literature review on Industry 4.0, addressing different aspects, such as technologies [5], [6], [7], intelligent manufacturing [8], sustainability [9], [10], [11], the COVID-19 pandemic [12],

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knowledge management [13], digital transformation (DT) [13], operations management [14], logistics [15], job shop scheduling [16], agri-food [17], smart manufacturing systems [18], circular economy [19], [20], predictive maintenance [21], supply chain [11], Internet of Things (IoT) [11], maturity models [22], and others [23]. Notably, there is a significant gap in the literature, as few studies have reviewed the application of Industry 4.0 in continuous production processes [24], [25]. Reference [26] underscores the scarcity of studies in the literature regarding the process modeling and simulation of realistic continuous systems within the framework of Digital Twins. In this context, continuous production processes present abundant opportunities for both research and practical application [27]. Recognizing the nuances of Industry 4.0 within continuous production processes is crucial, as highlighted by [28] and [29]. Nonetheless, there is a lack of literature on continuous process plants, as underscored in [2] and [30]. This dearth of available research emphasizes the imperative of increased investment in research and development to fully explore the potential of Industry 4.0 in continuous production processes, as reiterated by [31].

The mining industry also considers the challenges inherent to continuous processes. In 1998, Codelco and its Institute for Innovation in Mining and Metallurgy introduced continuous mining for caving operations, exemplifying potential future trends in mining operations toward continuous and automated processes [32].

The current literature on Industry 4.0 in the mining sector is rather scarce. Some studies have conducted comprehensive literature reviews on Industry 4.0, addressing different aspects, such as it mainly addresses key performance indicators [24], governance, standards, and regulation [25], sensing technology applications [26], water management [27], low-cost sensor technologies [28], technological and intellectual transition, [33] and reliability and fault analysis methods [34]. Notably, no studies were identified in this review that reviewed the literature on the application of Industry 4.0 in continuous processes in the mining industry.

According to [32], the future of mining is likely to be shaped by the adoption of continuous mining and automated operations, indicating a growing recognition of the significance of Industry 4.0 in the mining sector. As the mining industry has adopted these trends, it may face challenges and opportunities related to implementing digital technologies in continuous mining processes.

The mining sector transcends borders, with mineral resources considered the backbone of continents, as is the case in Africa [4]. Mining activities significantly affect the economy and have environmental consequences [4].

The German high-tech strategy associated with Industry 4.0, is applied in the raw materials sector through mining 4.0. This strategy involves advancing automation during extraction, transportation, and processing, aiming for economically efficient raw material production in countries with expensive labor [35]. This is crucial for efficient raw-material production, including sustainable practices and resource conservation [35].

Despite the significance of Industry 4.0, continuous production processes, and the mining industry, reviews specifically addressing these topics are lacking. This knowledge gap becomes apparent through searches in academic databases, such as Scopus and Web of Science. Highlighting this gap emphasizes the need for more comprehensive analysis in this area, suggesting a highly promising avenue for future research.

Therefore, this study conducts a systematic literature review to investigate Industry 4.0 in continuous processes in the mining industry, focusing on the relationship of Industry 4.0 design principles [36] (presented in Section II-A.) ((1) interconnection, (2) technical assistance, (3) information transparency, (4) decentralized decisions, and (5) sustainability), aiming to:

i) Identify and describe the application of I4.0 design principles to I4.0, to a continuous process in general and, in particular, in the mining industry.

ii) Synthesis Industry 4.0: opportunities for continuous processes within the mining industry.

iii) Encouraging discussions of future research directions.

The rest of the paper is structured as follows: Section II describes the theoretical background of Industry 4.0 in the context of continuous production processes in the mining industry. Section III describes the methodology used in the study. In Section IV, we present and discuss the results of the systematic literature review. Section V outlines the research gaps that formed the agenda. Finally, Section VI presents the conclusions of the study.

II. BACKGROUND

The following text provides a background for significant research on implementing Industry 4.0 within the mining industry 's continuous processes. It is compatible with the design principles of Industry 4.0, and proposes a set of definitions of basic concepts as a function of multiple authors in these aspects.

A. INDUSTRY 4.0 AND CONTINUOUS PROCESSES

In the last 30 years, the information technology revolution has radically transformed the world in which we live and work. In the XVIII and XIX centuries, the steam engine characterized the first industrial revolution (Industry 1.0) [37]. The second industrial revolution (Industry 2.0) materialized from the late XIX to the early XX century. It was characterized by mass production enabled by electric power, disruptive innovations such as light bulbs and telephones, and new industries built on steel and oil [38]. The third industrial revolution (Industry 3.0) was driven by computing power of computing (second half of the twentieth century), manufacturing automation through computerization, the rise of personal computers, and the Internet [39].

Discussions surrounding Industry 4.0 began in 2011 [40], [41]. Industry 4.0, an innovative concept, has revolutionized how technology can help improve productivity, efficiency, agility, modularity, customization, real-time data, integration, prediction, simulation, tracking, self-control, and intelligent learning of production processes [42].

Interpretations of the term industry 4.0, however, differ; there is no single definition [36]. Industry 4.0 presents notable obstacles, such as making current production systems flexible and adaptable while remaining robust and economically efficient [43]. Some authors [5], [9], [22], [36], [44], [45], [46], [47], [48], [49] have provided design principles regarding the implementation of Industry 4.0 [36], [50]. However, these principles have not been universally agreed upon. Owing to the different perceptions of the authors of the design principles, it is challenging to list all of them [51]. The number of principles was varied [44] **(Tab. 1)**.

Traditionally, production processes are characterized by the volume and variety of products, which are easily identified based on projects, tasks, batches, mass production, and continuous production [52]. With the advent of Industry 4.0, challenging terms related to continuous industries have been introduced, such as batch-1, single-batch, individualized manufacturing, and mass customization, with the aim of meeting the evolving demands in different markets [53], [54], [55].

The technological concept of Industry 4.0, which is broadly presented, is not restricted to specific types of industry [2]. However, differences were identified between the industries with continuous and discrete processes [52]. Continuous processes have inherent characteristics that are related to their modes of production [52] **(Fig. 1)**.

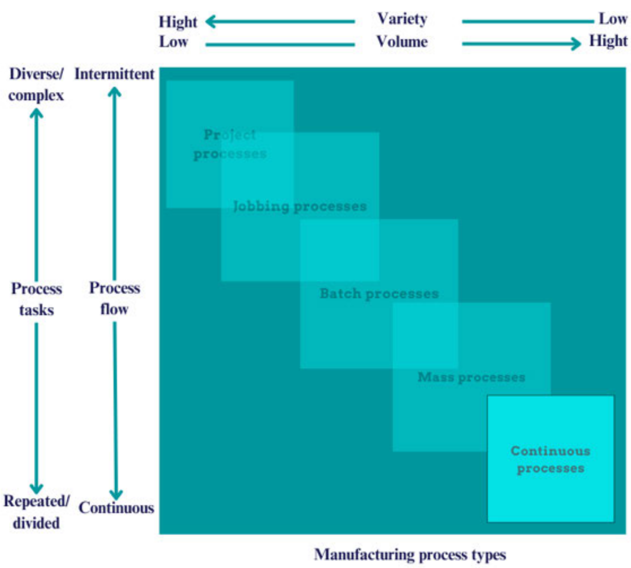

FIGURE 1. Characteristics of continuous processes. Adapted from [52].

TABLE 1. Design principles related to industry 4.0.

Author	Design Principles
[48]	Interest-Free Banking Fintech Robotics in Banking Omni-Channel (O-C) Open Banking (OB)
[9]	Interoperability Modularity Decentralization Virtualization Real-time capability Service Orientation Horizontal Integration Product and service individualization Smart Factory Smart Product Vertical Integration
[5]	Interoperability Modularity Virtualization Real-time capability Service Orientation Local
[49]	Interoperability Modularity Decentralization Virtualization Real-time capability Service Orientation
[36]	Interconnection Decentralized Decisions Information Transparency Technical Assistance
[44]	Interoperability Modularity Decentralization Virtualization Real-time capability Human aspect
[46]	Interoperability Modularity Decentralization Virtualization Real-time capability Service Orientation Eco-design
[47]	Interoperability Modularity Decentralization Virtualization Real-time capability Service Orientation.
[56]	Interconnection Decentralization Real-time capability Technical Assistance Continuous sustainable performance evaluation

The digitization of process chains in discrete manufacturing has been widely studied, particularly in the automotive industry [57]. However, these studies do not fully reflect the reality of process industries [2], [30]or require more investment in R&D [31]. In continuous processes, assigning a unique identification to each object is challenging, compromising the comprehensive inspection of the quality of the production process [58].

Advantages of flow processes over batch systems include productivity, heating, mixing efficiency, safety, and reproducibility [59]. Reference [60] explained that continuous processes are a promising strategy for competitiveness in the chemical industry because of the possibility of better product uniformity and because they can significantly reduce the consumption of raw materials and energy. These characteristics demand fluidity, agility, and flexibility in continuous production lines in order to align with the company's strategies [61], [62]. Identifying the cause of specific deviations during production is more difficult, as the product flows continuously through different operations [60].

No study explicitly addresses the design principles in this systematic literature review (SLR) of the design principles for implementing Industry 4.0 in continuous production processes, particularly in the mining industry. However, the fundamental study in [36] is widely referenced in literature as the basis for understanding these principles. Furthermore, sustainability was included as a design principle given its importance in implementing and maintaining Industry 4.0 [44], [45], [46], which is mainly a continuous industry [54], [63], [64], [65], [66]. Thus, in addition to the design principles proposed by [36], this study included sustainability in Industry 4.0, focusing on the continuous process industries in the mining industry (**Fig.2**).

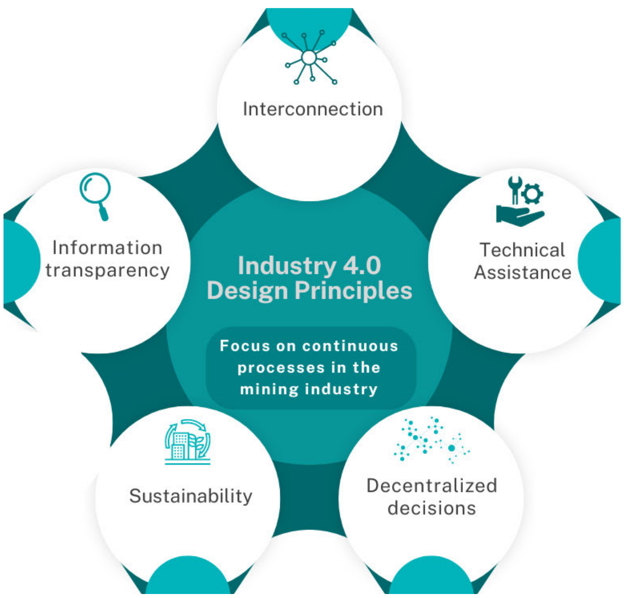

FIGURE 2. Theoretical framework.

The concepts of Sustainability and Sustainable Development (SD) can be regarded as umbrella constructs that encompass economic, environmental, and social dimensions [67] and have been adopted by the business community [68]. Many authors have highlighted the importance of Industry 4.0 systems being sustainable by enhancing communication and information flows [69], promoting knowledge sharing and collaborative work [70], improving production efficiency and productivity, reducing costs [70], supporting novel business models and Quality 4.0 (combination of quality management and improvement models and approaches with technology) and improving quality and customer satisfaction [71], and when combined with improvement methodologies (e.g., Lean), Industry 4.0 improves employee morale, reduces lead time, improves product quality, customizes products, and reduces waste [72].

B. INDUSTRY 4.0 AND MINING

Despite the risks associated with mining operations, it is one of the oldest and the most significant industries. Except for large international corporations, many mining operations have delayed the adoption of modern technology [73].

By incorporating digitization and Industry 4.0, concepts in mineral mining and processing industries are becoming increasingly essential. Digital technology can enhance the efficiency, safety, and sustainability of mining and processing [74]. By leveraging data analytics, real-time monitoring, and automation, mining processing plants can achieve higher productivity and reduce environmental impact [74].

The main objectives of Mining 4.0 result in specific technological goals, including developing robust sensors, machine-to-machine (M2M) communication, and artificial intelligence [35]. In addition to these core technologies, other requirements for future mining projects encompass issues such as safety, environmental impact, cost efficiency, and social acceptance [35]. Initiatives such as the German Information Society 2010 (iD2010) and the ICT 2020 research promotion program highlight the importance of Internet of Things (IoT) and M2M communication, identifying key research needs and economic opportunities [35].

However, because of the resistance of rocks in most metal ore deposits, mechanical extraction methods are often unfeasible, necessitating drilling and blasting techniques. This, in turn, impairs continuous operation [32], [75].

The continuous mining stage involves grinding. This continuous production complexity necessitates real-time process control and a consistent material flow across all zones [76]. A significant challenge in milling is the immense energy consumption required to produce particles smaller than micron size [77]. Comminution, a controlled size-reduction process, is employed in mining plants to achieve the desired particle size. However, conventional grinding methods, such as tumbling ball mills, are energy-intensive, particularly when producing submicron particles [77]. Energy efficiency represents an area where Industry 4.0 technologies can make significant advances, allowing for sophisticated monitoring and optimization of processes. Increases in productivity and improvements in operational efficiency are primary drivers of innovation. Therefore, the development of continuous systems for material extraction and movement beyond the coal sector is likely to become important in the future [32].

III. METHODOLOGY

Given the transformations that have taken place in industries over the last decade [78], [79], [80], and the significance of the mining industry, it is important to identify and summarize the current state of the relationship between Industry 4.0 and continuous production processes within the mining industry.

Specifically, the search for the intersection of 'Industry 4.0,' 'continuous processes,' and 'mining industry' yielded few relevant articles [80]. Due to the lack of identified studies on Industry 4.0 in continuous processes within the mining industry, we conducted two simultaneous systematic reviews: Context 1 focused on Industry 4.0 in continuous processes in general. In contrast, context 2 concentrates on the continuous production processes of the mining industry (**Fig. 3**). This approach was crucial to address the observed scarcity of studies on integrating Industry 4.0 in continuous processes in the mining sector.

This dual approach was designed to initially identify evidence linking each context with Industry 4.0, the constituent elements of Industry 4.0, within each context, and the challenges and facilitators of Industry 4.0. These steps aim to gain insights into patterns, distinctions, and unique potential applications for this sector and to develop a conceptual framework based on the opportunities and learning of Industry 4.0 in continuous processes for the mining industry.

The initial phase of the investigation focused on understanding the basic principles of continuous processes and the integration of Industry 4.0, thereby establishing a solid foundation for more detailed analyses within the mining industry.

As illustrated in **Fig. 3**, this comprehensive methodology allows for a systematic examination of the existing literature and practices, facilitating a detailed understanding of how Industry 4.0 can be effectively implemented in continuous processes, particularly in mining operations.

A systematic literature review was conducted to comprehensively evaluate and interpret all available research relevant to a specific research question, topic area, or phenomenon of interest [81], [82]. Following the methodology proposed in [81] and [82], the systematic literature review consisted of three main phases: planning (Topic III. A), conducting (Topic III.B), and reporting (Section IV, Results and Discussion). The guidelines provided by [80] and [81] have been widely adopted in computer science and engineering literature, as evidenced by numerous studies [83], [84], [85].

A. PLANNING THE REVIEW

At this stage, the research question and the corresponding methodology are outlined. Within the broad domain of investigating the implementation of Industry 4.0, the main objective is to understand how academic literature treats Industry 4.0, in the continuous production processes of the mining industry.

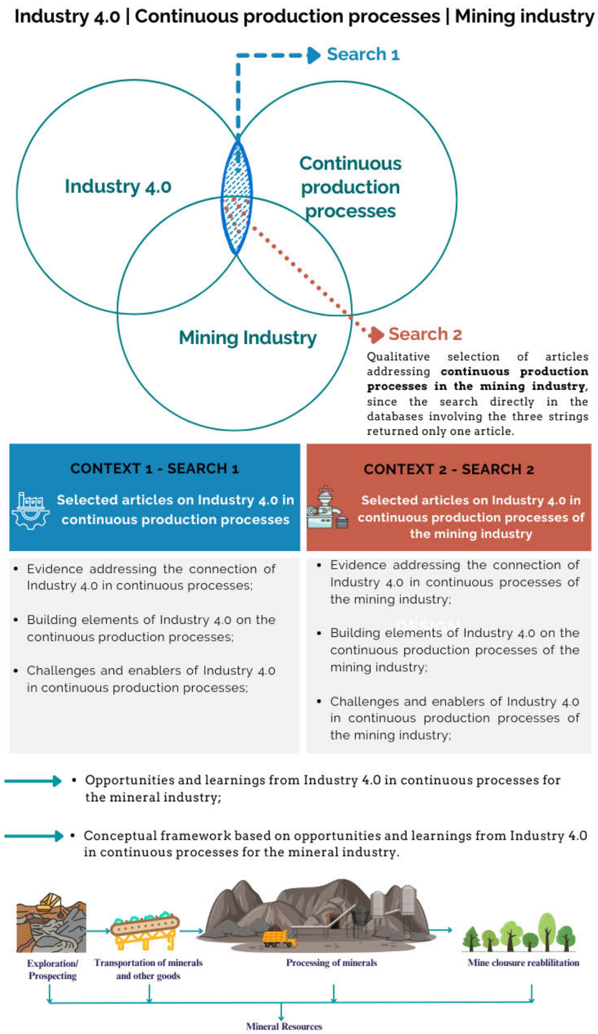

FIGURE 3. **Diagram illustrating the dual focus of the study methodology: Context 1 (Industry 4.0 in general continuous processes) and Context 2 (continuous processes in the mining industry).**

Thus, the following five research questions **(R.Q.)** emerged, identified from **R.Q.1** to **R.Q.5**:

R.Q.1: What evidence exists of a connection between Industry 4.0 and continuous processes, and how is this connection explored within the mining industry?

R.Q.2: What are the building elements of Industry 4.0 in continuous production processes, particularly within the mining industry?

R.Q.3: What are the main research topics addressed in studies related to Industry 4.0 in continuous production processes, particularly within the mining industry (Contexts 1 and 2)?

R.Q.4: What are the challenges faced in implementing Industry 4.0 in continuous production processes, particularly within the mining industry?

R.Q.5: What knowledge gaps exist in the literature, and what opportunities for future research can be identified?

Two different approaches were used:

1) Bibliometric review: Quantitative analysis of the number of published articles, identifying the principal authors and co-references on related topics, annual scientific production, three-field plots, core sources, Bradford's law, and the most globally cited documents. Bibliometric methods have the potential to establish a systematic and transparent review process, which can be replicated by other researchers [86]. These methods are considered beneficial for enhancing the quality of the analyses, particularly in literature reviews. They serve as valuable tools by providing guidance before detailed reading and assisting researchers in identifying the most influential work in each field. They help acquire a comprehensive view of the existing literature [86], [87]. Furthermore, this objective approach in bibliometric analysis contributes to impartially mapping the research landscape and minimizing the introduction of subjective bias in interpretations [86]. At this stage, we selected appropriate bibliometric software to conduct the research. The choice was based on the R programming language and the RStudio graphical interface [88], aiming to make R programming more accessible and efficient. These resources enabled the execution of data cleaning and removal of duplicate studies, and facilitated the integration of a unified table into Biblioshiny [89], a package developed for the R language. Other bibliometric analysis software such as VOS Viewer [90] can be used.

2) Qualitative literature review: Based on the content allowed, the relationship between Industry 4.0 and continuous production processes, their advantages, challenges, and gaps. The selection process for the primary studies was facilitated using an online parsifal tool (bibliometric metadata) [91]. This choice was motivated by its suitability for collaborative usage among multiple users via the Web. Parsifal's user-friendly interface enabled the selection of articles based on the predetermined inclusion and exclusion criteria. In addition, Parsifal allowed the extraction of a final spreadsheet with primary articles, which was also used to search for articles in academic databases. Subsequently, data extraction was performed on the basis of the full content of each selected article.

The selection of two research databases for the study was based on a careful analysis and filtering of data from relevant documents. We chose the Scopus (https://www.scopus.com) and Web of Science (WoS) (https://www.webofscience.com) databases because of their widespread recognition and frequent use in review articles in the field of industrial engineering. Such platforms are expected to provide pertinent and reputable research [85], [92], [93]. These platforms index articles from respected and widely-used sources, particularly in fields such as electrical engineering, computer science, telecommunications, and other areas related to technology and innovation, as is the case with IEEE Xplore. In addition, Scopus and the Web of Science offer access to dependable data, metrics, and analytical tools to effectively execute bibliometric reviews. In fact, within what is researched, they are the only ones that offer a base of cited articles necessary for most studies. The publication period was 2011 to 2024, and this study was conducted in April 2024. The inclusion of 2011 was motivated by the fact that it was in that year that the term 'Industry 4.0' began to gain prominence in Germany [40], [41]. Additionally, the inclusion of only English-language studies was restricted.

This dual-database approach strengthens the data set, increasing the accuracy and comprehensiveness of the bibliometric analysis.

The following search string considered "keywords related to Industry 4.0" [36], [40], [41], [47], "keywords related to continuous production processes," [26], [52], [94], [95], [96], [97], [98] and "keywords related to the mining industry (continuous processes)."

The application of the snowballing technique was essential for refining the search string, enabling the incorporation of articles identified through this method and testing its effectiveness by expanding the range of results. Additionally, the snowballing process played a key role in forming an initial understanding of the research field, providing a comprehensive overview of the exploratory literature related to the constructs of Industry 4.0 and continuous processes in the mining industry. The selection of keywords was further enriched by consultations with researchers specialized in the field of Information Technology, members of the research group to which the authors are affiliated. These experts played a crucial role in clarifying and refining the most appropriate terms for the search. This procedure was instrumental in defining the keywords to be applied in the search filters, ensuring the adequacy and accuracy of the article selection.

1) "Industry 4.0", "Intelligent manufacturing," "Smart manufacturing," "Industrial Internet of Things," and "Smart production";
2) "Continuous flow," "Continuous industry," "Continuous production", and "Continuous processes.
3) "Mining industry," "Comminution," " Minerals processing," and "Cushing."

B. CONDUCTING THE SYSTEMATIC REVIEW

Data were collected during the second stage of this systematic review. Articles were identified and excluded based on their titles and abstracts to obtain primary articles and critically evaluate the studies. As presented in **Fig. 3**, this research was divided into two distinct stages to fill the gap in studies related to Industry 4.0 in continuous processes in the mining industry.

Thus, **Tab. 2** and **Tab. 3** presents the search terms used to identify each context (1 and 2) in each scientific database.

The articles were selected from databases that included articles and reviews. The inclusion (I) and exclusion (E) criteria were established, as outlined in **Tab. 4**. To handle uncertainties in the selection process, when co-authors had divergent opinions, these divergences were addressed not only among the authors but also with other researchers from the research group focused on information technology, which

TABLE 2. Search terms used in scopus and WoS databases - Context 1.

Context/ Database	Search terms
Context 1 Scopus	(TITLE-ABS-KEY ("Industry 4.0" OR "intelligent manufacturing" OR "smart manufacturing" OR "industrial internet of thing" OR "smart production")) AND TITLE-ABS-KEY ("continuou* productio*" OR "continuou* flow" OR "continuou* industr*" OR "continuo* proces*") AND PUBYEAR > 2010 AND PUBYEAR < 2025 AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "re")) AND (LIMIT-TO (LANGUAGE , "English"))
Context 1 WoS	"Industry 4.0" OR "intelligent manufacturing" OR "smart manufacturing" OR "industrial internet of thing" OR "smart production" (Topic) and "continuou* productio*" OR "continuou* flow" OR "continuou* industr*" OR "continuo* proces*" (Topic) and Article or Review Article (Document Types) and English (Languages) https://www.webofscience.com/wos/woscc/summary/559bb09a-b3df-41ca-8718-1c71ddf7e398-e072376b/relevance/1

TABLE 3. Search terms used in scopus and WoS databases - Context 2.

Context/ Database	Search terms
Context 2 Scopus	(TITLE-ABS-KEY ("Industry 4.0" OR "intelligent manufacturing" OR "smart manufacturing" OR "industrial internet of thing" OR "smart production") AND TITLE-ABS-KEY ("mining industry" OR "comminution" OR "mineral* processing" OR "crushing")) AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "re")) AND (LIMIT-TO (LANGUAGE , "English"))
Context 2 WoS	"Industry 4.0" OR "intelligent manufacturing" OR "smart manufacturing" OR "industrial internet of thing" OR "smart production" (Topic) and "Mining industry" OR "comminution" OR "mineral* processing" OR "crushing" (Topic) and Article or Review Article (Document Types) and English (Languages) https://www.webofscience.com/wos/woscc/summary/879b6cfa-62cf-4472-9756-8570d450b5c7-e4c83f60/relevance/1

holds regular meetings for alignment and discussion, seeking consensus among the authors and ensuring consistency and agreement in the selection process.

Note that articles that presented the concept of ''Continuous Flow'' associated with the Toyota Production System and the Lean Manufacturing (LM) methodology were not considered, as these refer to the organization of the production process in such a way that materials or products flow in a step to another with a minimum of intermediaries or intermediate actions. For example, this study [99] was excluded from analysis [76]. Although the term refers to the LM, some authors have used a concept similar to that proposed in [52], which is why it was used as a search string.

Articles related to pharmaceutical ''continuous manufacturing'' were excluded from the analysis. In recent years, efforts have intensified in the pharmaceutical industry to transition from batch to continuous production, along with digitalization in process development [100], [101], [102].

TABLE 4. Inclusion (I) and Exclusion (E) criteria.

	Criteria
I1	Articles about Industry 4.0 and continuous production processes.
I2	Articles about Industry 4.0 and continuous production processes and the mining industry.
E1	Duplicate articles due to search in two separate databases.
E2	Articles that superficially approached Industry 4.0, using the terms only in the title, abstract, keywords, or references, without in-depth exploration of the theme.
E3	Articles in which the term “continuous production” is not related to the type of production process proposed by [52], as is the case of “continuous production maintenance”, “innovation as a continuous process” and “continuous process enhancement”.
E4	Articles that presented the concept of “continuous flow” associated with the Toyota Production System and the Lean Manufacturing methodology.
E5	Articles presenting the concept of "continuous manufacturing" and “continuous pharmaceutical manufacturing processes” associated with small-scale production in the pharmaceutical industry.

This transition is motivated by the many benefits of the continuous process, such as rapid capacity adjustment, reliable quality assurance, and improved heat and mass transfer, which positively affect conversion, safety, and reproducibility [100], [101], [103]. These processes have specific characteristics. For example, they involve regulatory authorities and ethical and technical issues in the drug approval process [104]. This study focused on continuous mass-production processes, as presented in [52], where materials are processed in a continuous flow that goes through successive stages, which generates a single product or a few similar products, very high volume, very low flexibility, and integrated processes.

Tab. 5 and **Tab. 6** presents in detail the number of articles obtained in each of the academic bases for each context (1 and 2) after adding the search terms, considering the language filters (English), date (2011-2024), and type of document (Articles and Review articles).

TABLE 5. Number of articles in the scopus and WoS databases – Context 1 - Industry 4.0 and continuous processes.

Search terms	WoS	Scopus
(“Industry 4.0” OR “Intelligent manufacturing” OR “Smart manufacturing” OR “Industrial internet of thing” OR “Smart production”) AND (“continuous production” OR “continuous flow” OR “continuous industry” OR “continuous processes”)	46	54
Removal of 37 duplicate articles using RStudio. From here onwards, a single data spreadsheet was used.	63	

The articles listed in **Tab. 5** and **Tab. 6** was reviewed, including titles, abstracts, and full texts, by applying the inclusion and exclusion criteria (**Tab. 3**).

The selection of the final works for review was carried out based on a systematic data extraction process,

TABLE 6. **Number of articles in the scopus and WoS databases – Context 2 - Industry 4.0 in the continuous processes of the mining industry.**

Search terms	WoS	Scopus
("Industry 4.0" OR "Intelligent manufacturing" OR "Smart manufacturing" OR "Industrial internet of thing" OR "Smart production") AND ("Mining industry" OR Comminution OR "Minerals processing" OR Crushing)	43	60
Removal of 34 duplicate articles using RStudio. From here onwards, a single data spreadsheet was used.	69	

as recommended by [82] and [104]. The process was carefully planned with a focus on the research questions, aiming to highlight the differences and similarities in the study results. The selection of works was conducted according to the following criteria:

i) Whether the article could be related to any of the design principles of Industry 4.0 in continuous processes, such as Interconnection, Technical Assistance, Decentralized Decision-Making, Sustainability, and Information Transparency. When applicable, these principles were identified in the article.

ii) Whether the article used technologies related to Industry 4.0. If so, the relevant technologies were identified.

iii) Whether the article presented the challenges and enablers for the implementation of Industry 4.0 in continuous processes in the mining industry. If so, these factors were identified to be further discussed.

These elements were carefully selected to provide a comprehensive and in-depth analysis of the studies, allowing for a meaningful and coherent synthesis of relevant information.

Once any of the key elements mentioned above were identified, the approval information for the articles was recorded in the online Parsifal tool, facilitating the identification of approved studies and the organization of the research. The approved articles had their metadata extracted for quantitative analysis, using Biblioshiny. For the qualitative analysis, the results of the defined criteria were integrated into the results of this article and were subsequently interpreted and analyzed based on the graphs, as summarized in **Fig. 4**.

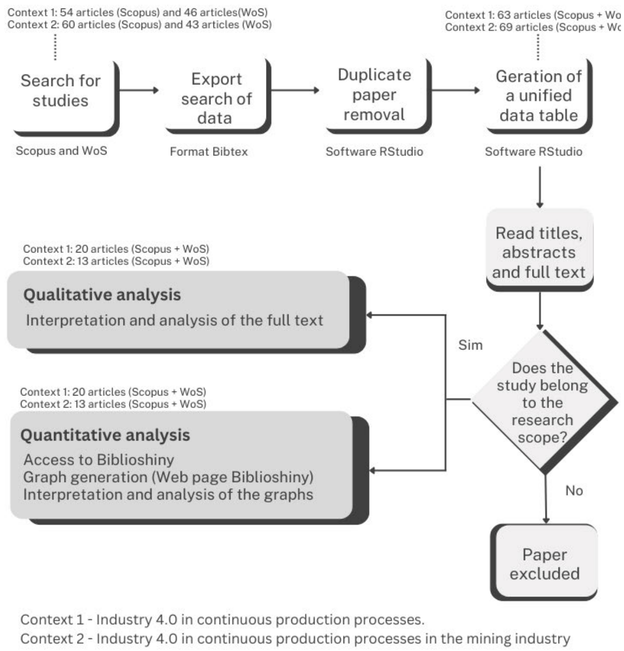

FIGURE 4. **Workflow of the bibliometric literature review.**

IV. RESULTS

This study aimed to answer Research Questions **R.Q.1** to **R.Q.4**. Section A describes the answer to **R.Q.1**, in which bibliometric data analysis was used. In the following sections, **R.Q.2** and **R.Q.4** are addressed by considering the content analysis strategy presented in the methodology. **R.Q.5** has been included in the discussion of the results.

A. R.Q.1: WHAT EVIDENCE CONNECTS INDUSTRY 4.0 TO CONTINUOUS PROCESSES AND ITS APPLICATION IN THE MINING INDUSTRY?

This topic is relevant for addressing question **R.Q.1** and demonstrates the relationship between the concepts of the Fourth Industrial Revolution or Industry 4.0, a continuous process, and the mining industry. **Tab. 7** presents the bibliometric data of the articles selected for analysis.

Fig. 5 shows a recent and periodic increase in articles on Industry 4.0 and continuous production processes; the first article identified in this analysis was published in 2019, with a notable increase in 2023, when six articles were published.

The results of this investigation identified 13 academic articles that address continuous processes in the mining industry from the perspective of Industry 4.0 (**Fig. 6**), with the first article dated 2017 and a notable increase in 2020, with the publication of five articles.

TABLE 7. **Number of articles and search terms used in Scopus and WoS databases.**

Description	Results Context 1	Context 2
Timespan	2019:2023	2017:2024
Sources (Journals, Books, etc)	17	13
Documents	20	13
Annual Growth Rate %	-24.21	10.41
DocumentAverage Age	2.65	2.77
Averagecitations per doc	9.5	12.85
References	36	0
Keywords Plus (ID)	242	103
Author's Keywords (DE)	111	65
Authors	75	54
Authors of single-authored docs	2	0
Single-authored docs	2	0
Co-Authors per doc	3.75	4.69
Internationalco-authorships %	0	0
Article	19	11
Review	1	2

Notably, there is a considerable gap between the emergence of the term "Industry 4.0" in 2011 [40] and the identification

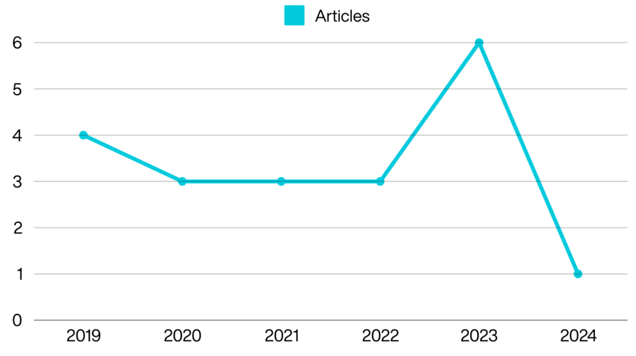

FIGURE 5. Annual scientific production – Context 1 - Industry 4.0 in continuous production processes.

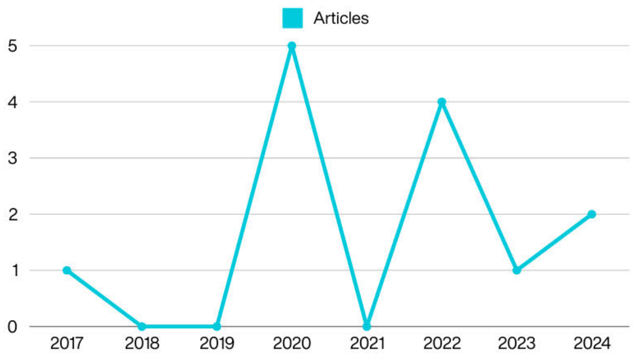

FIGURE 6. Annual scientific production – Context 2 - Industry 4.0 in continuous production processes in the mining industry.

TABLE 8. Most relevant sources – Context 1 – Industry 4.0 in continuous production processes.

Sources	Articles
Computers in Industry	2
IEEE Access	2
Sensors	2
Applied Soft Computing Journal	1
Electronics (Switzerland)	1
IEEE Robotics and Automation Letters	1
Industrial and Engineering Chemistry Research	1
Informatica (Slovenia)	1
Izvestiya of Saratov University Mathematics Mechanics Informatics	1
Journal of Intelligent Manufacturing	1

TABLE 9. Most relevant sources –Context 2 – Industry 4.0 in continuous production processes in the mining industry.

Sources	Articles
Applied Sciences (Switzerland)	1
Computers and Chemical Engineering	1
Engineering Applications of Artificial Intelligence	1
IEEE Access	1
IEEE Transactions on Industrial Informatics	1
International Journal of Advanced Manufacturing Technology	1
International Journal of Emerging Technology and Advanced Engineering	1
International Journal of Product Lifecycle Management	1
Journal of Engineering and Applied Sciences	1
Material and Mechanical Engineering Technology	1

of the first study in each context: eight years for context 1 (**Fig. 5**) and six years for context 2 (**Fig. 6**). This gap suggests a delay in research on this topic. Despite the limited number of articles, academic interest in this subject is still evident.

Tab. 8 demonstrates the sources of articles related to Industry 4.0 and continuous production processes. Similarly, **Tab. 9** illustrates the sources of articles related to Industry 4.0 and continuous production processes in the mining industry. This approach provides a view of the distribution of studies in the literature, enabling the identification of patterns and understanding of the relevance of different sources in research. These sources also serve as key references for researchers to submit for their studies.

The top 20 globally cited documents (**Tab. 10 and Tab. 11**) seek to identify the studies that have dealt with the new themes in the literature: ''Industry 4.0, Continuous Processes, and ''Industry 4.0, in Continuous Processes in the Mining Industry.'' Understanding changes in citation trends in literature can provide important information on the location of research might be going. The primary rationale behind this approach is to chart the influence of extant work, leading to a more expansive and informed perspective on the current understanding of niche fields.

Context 1: When we analyzed the most globally cited documents, as shown in **Tab. 10**, documents that stand out in the studied theme are identified. The study by [105] appears with 46 citations (Scopus), [58] with 22 citations (Scopus), and [80] 21 citations (Scopus). Reference [105] presented a reinforcement learning decision model for online process parameter optimization from offline data in injection molding. Reference [58] presented an automatic virtual metrology method for carbon fiber manufacturing.

Context 2 – Studies addressing Industry 4.0, in continuous processes within the mining industry, are presented in **Tab. 11**. Reference [32] (69 citations Scopus), [106] (42 citations Scopus), [80], [107] (21 citations Scopus). Reference [32] presented innovations in the Mining Industry and technological trends (including Continuous Mining). Reference [106] presents the real implementation of a neural network-based Model Predictive Control (NNMPC) scheme to control an industrial paste thickener. Reference [107] presented a multiple regression analysis for predicting extraction efficiency in the mining industry with industrial IoT, while [80] developing and implementing performance indicators for aggregate production using dynamic simulation, focusing on continuous processes (crusher, screen, bin, and conveyor).

TABLE 10. Most global cited documents – Context 1 – Industry 4.0 in continuous production processes.

ID	Article	DOI	Total Citations
1	[105]	10.1016/j.asoc.2019.105828	46
2	[58]	10.1109/LRA.2019.2917384	22
3	[80]	10.1016/j.mineng.2019.106065	21
4	[108]	10.1021/acs.iecr.1c00209	17
5	[109]	10.3390/s23031263	16
6	[61]	10.1108/JMTM-10-2018-0361	15
7	[76]	10.1109/ACCESS.2022.3211288	11
8	[60]	10.3390/s19225009	8
9	[110]	10.31803/tg-20200706131623	8
10	[2]	10.3390/su11051490	7

TABLE 11. Most global cited documents – Context 2 – Industry 4.0 in continuous production processes in the mining industry.

ID	Article	DOI	Total Citations
1	[32]	10.1007/s42461-020-00262-1	69
2	[106]	10.1109/TII.2019.2953275	42
3	[107]	10.1007/s11740-020-00970-z	21
4	[80]	10.1016/j.mineng.2019.106065	21
5	[111]	10.3390/app12147298	4
6	[112]	10.1109/ACCESS.2022.3226942	3
7	[113]	10.46338/ijetae1022_14	3
8	[114]	10.1504/ijplm.2022.125818	3
9	[115]	10.1016/j.compchemeng.2023.108476	1
10	[116]	10.3390/min13111445	0

B. R.Q.2: WHAT ARE THE BUILDING ELEMENTS OF INDUSTRY 4.0 IN CONTINUOUS PRODUCTION PROCESSES, PARTICULARLY WITHIN THE MINING INDUSTRY?

While companies globally adopt technological changes to integrate digital solutions into their supply chains, the main challenges and requirements of Industry 4.0 extend beyond technology alone, encompassing areas such as standardization, work organization, and the development of new business models [61].

1) INDUSTRY 4.0 DESIGN PRINCIPLES

No studies were found either in the primary articles (Context 1 (21) and Context 2 (13)) or in the co-references identified in these studies, which explicitly addressed the design principles for implementing Industry 4.0 in continuous production processes or continuous mining processes. A qualitative analysis was conducted by thoroughly reading the articles to identify the principles for implementing Industry 4.0 in continuous mining processes, addressing this research gap. The study in [36], which is widely referenced in literature, served as the basis. Furthermore, as explained in Section I, sustainability was included as a design principle given its crucial role in implementing and maintaining Industry 4.0 [45], [46].

R.Q.2 disclosed the constructive elements of Industry 4.0 in continuous production processes. Analyzing the sample of selected articles from the perspective of Industry 4.0, design principles — that is, "how to implement" Industry 4.0 — **Fig. 7** and **Fig. 8** illustrate the distribution of articles across Contexts 1 and 2. These contexts consider principles such as technical assistance, interconnection, sustainability, information transparency, and decentralized decision making.

Thus, this systematic literature review demonstrates the connection between Industry 4.0, and continuous production processes from the five design principles identified for implementation (**Tab. 12**) Sustainability, Interconnection, Technical Assistance, Decentralized Decisions, and Information Transparency.

In both Contexts (1 and 2), the design principle of Technical Assistance appears most frequently, demonstrating its importance and the interest of the selected articles in this systematic review in guiding both continuous industries and the continuous mining industry toward Industry 4.0.

Each principle is discussed in detail in the following section, and opportunities that can be investigated are presented.

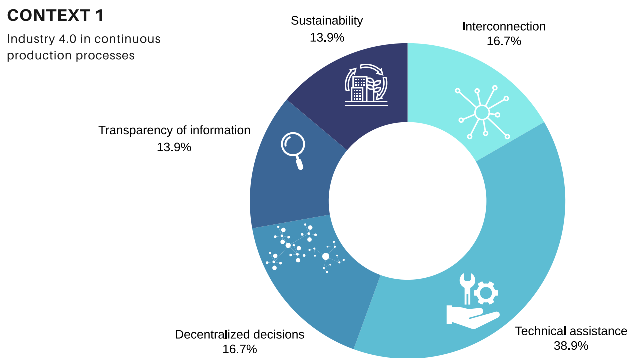

FIGURE 7. Article by designs principles – Context 1 – Industry 4.0 in continuous production processes.

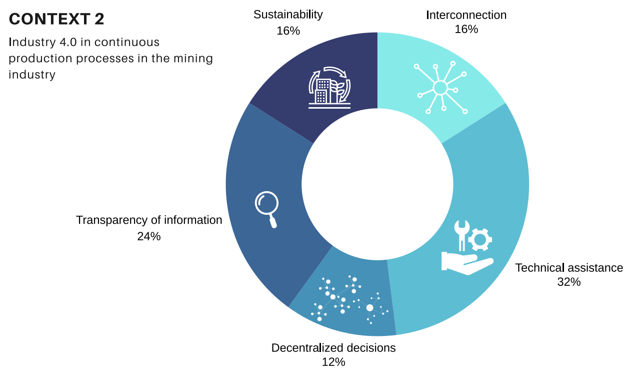

FIGURE 8. Article by design principles – Context 2 – Industry 4.0 in continuous production processes in the mining industry.

a: INTERCONNECTION

Interconnection is a prerequisite for the other principles [36]. Thus, we have presented the contributions of the authors to each context.

TABLE 12. Number of articles and search terms used in Scopus and WoS databases.

Design Principle	Context 1/ Author	Count	Context 2/ Author	Count
Interconnection	[2], [24], [60], [76], [108], [117], [115], [63]	8	[32], [107], [118], [114]	4
Technical Assistance	[2], [24], [26], [58], [60], [61], [63], [64], [110], [119], [120], [121], [122], [80] , [109]	15	[80],[106], [107], [112], [113], [115], [118], [123]	8
Decentralized Decisions	[24], [27], [58], [61], [105], [109]	6	[112], [124], [125]	3
Information Transparency	[58], [117], [121],[76]	5	[107], [115], [124], [125], [123], [116]	6
Sustainability	[32], [2], [63], [64], [119]	5	[124],[116], [111], [114]	4

-Context 1 - Industry 4.0 in continuous production processes: The installation of sensors may be impossible at certain stages of the continuous process. To help with this aspect, [2] used a semi-automation method and flexible structure production control (FSPC) to assist in real-time preventive measures formulated for a crusher process that is impossible to automate.

Reference [24] conducted a review of the main challenges of the Industry 4.0 paradigm in the downstream oil and gas sector. They highlighted that integrating legacy systems with modern communication and data-processing technologies poses a significant challenge that hinders the effective implementation of data analytics initiatives. Cybersecurity issues and operational requirements complicate their application to projects. Similarly, the complexities of downstream processes and inherent uncertainties often challenge current machine-learning approaches, necessitating system explainability and accountability improvements for the effective deployment of artificial intelligence technologies.

Continuous production processes face a series of challenges in adapting to the era of Industry 4.0, as highlighted by [24]: i) data transmission flexibility: dynamically managing the latency and temporal instability of each signal is crucial; ii) Scalability: Large-scale sensor deployment requires highly dense network infrastructure; iii) Reliability: Ensuring precise and timely data delivery is essential; v) Security: The expansion of wireless communications significantly increases exposure to risks; iv) Ubiquity: Many devices in industrial facilities rely on wired communications, which can result in additional costs and delays when making infrastructure modifications.

Reference [60] discusses the challenge of obtaining commercial sensors capable of providing real-time information, exemplified by monitoring rheological properties and velocity profile measurements. Rheological properties are typically measured using rheometers that are often offline laboratory devices [60]. Current real-time viscosity measurements require continuous maintenance, are generally invasive, and may interfere with the process layout, providing rheological information only for liquids near the surface of the projecting device. Thus, [60] a hybrid approach that combines a physics-based ultrasonic post-processing algorithm with the principal is proposed for data reduction. Subsequently, a neural network algorithm was explored to correlate the principal components of the principal component analysis with the key points.

Reference [76] proposed a holistic approach for SCADA systems implemented to control continuous-flow production in the steel industry. They emphasized that in this industrial environment, the SCADA system's design, development, and deployment are significantly influenced by the specificities of the continuous-flow production process and the extreme physical conditions under which the Industrial Control System (ICS) operates. This necessitates real-time process control and the continuous maintenance of material flow throughout all production zones.

Reference [117] introduced a model IoT platform to gather data generated in a continuous manufacturing plant. This includes data from mobile devices and event-related potential (ERP) systems. These data were analyzed using machine learning and artificial intelligence technologies, resulting in visualization of key performance indicators (KPIs). In addition to the proposed platform concept, a prototype was developed for cement factories, which represents a central continuous process in the manufacturing industry.

Reference [108] introduced a real-time optimization algorithm designed to manage production rates at a chemical industrial site, aiming to meet diverse customer demands. This study highlights the successful integration of control systems and a facility's sales department, enabling more dynamic and responsive interactions.

- Context 2 – Industry 4.0 in continuous production processes in the mining industry: Reference [32] highlights a problem that precedes the implementation of Industry 4.0 principles in the continuous processes of the mining industry. The authors present a case study of the Continuous Mining System (CMS), an innovation project developed by Codelco in Chile, which aimed to create a continuous material handling system for block and panel excavation operations but was discarded because of the difficulties faced in the construction phase for its industrial validation. Reference [32] emphasized that although the process of adopting and incorporating a set of tools, known as Technology 4.0, in the mining industry is often mentioned as one of the main concerns among most large-scale mining companies, the level of digitalization in the industry remains low, indicating that much of the potential for digital transformation in the sector remains untapped. Among the highlighted challenges are commitment to and coordination of joint tasks among different business units, organizational structures, and cultural mindsets.

Reference [107] conducted a study on a pilot-scale mixer-settler cascade, which was used to evaluate the recovery of zinc contained in zinc sulfide leach liquor in continuous operation. They incorporated an IoT module that allows efficient real-time tracking and provides crucial information for greater control and predictive services. In addition, it promises a higher performance, energy efficiency, reduced latency, faster response time, scalability, and better regional accuracy in the mining industry.

An oversized destruction Process in the Rock Supply Line for Primary Crushing was automated in [118]. The authors conducted a study on the process of transportation to the jaw crusher before crushing the rock into medium particles. They suggested inserting sensors (laser emitter and receiver) behind the sidewall of the crusher inlet directly into the crusher throat toward the movement of the material. This setup allows the sensors to gather data on the material movement immediately and provide rapid feedback.

Fig. 9 presents a graphic summary of the main themes highlighted in the articles on the principle of interconnection, Industry 4.0, in continuous production processes in the mining industry.

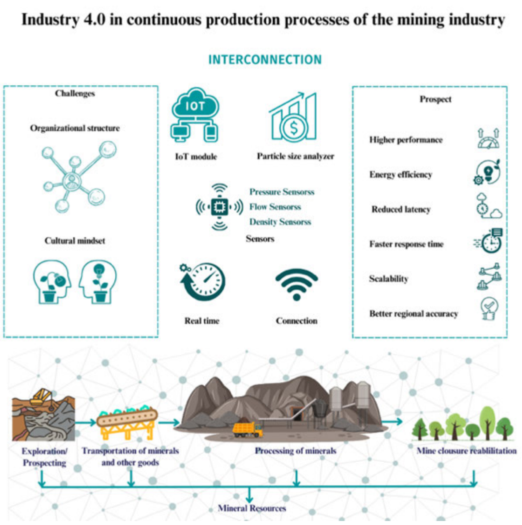

FIGURE 9. Graphic summary of the main themes highlighted in the articles - Context 2 - Principle of interconnection - Industry 4.0 in continuous production processes in the mining industry.

b: TECHNICAL ASSISTANCE

Context 1 - Industry 4.0 in continuous production processes: In continuous processes, monitoring restricted to specific equipment may not detect all the effects of operational conditions. For instance, an increase in the bearing temperature of a pump due to a disproportionate feed load may go unnoticed [119]. Therefore, an approach [119] employing data mining and machine learning techniques for analysis and anomaly detection in a production system was proposed. Collecting and analyzing operational data and equipment health monitoring information makes it possible to identify variables responsible for abnormal conditions, enabling preventive actions to enhance system reliability.

Reference [26] developed a customized modeling methodology for continuous industrial processes based on material flow networks, and implemented it using a dedicated process simulation tool. This approach enables system monitoring and analysis, performance optimization, and correction of undesired behavior. It includes system monitoring, root cause analysis, limitation, performance optimization, and recovery of the system behavior.

Reference [110] proposed the Lean Smart Maintenance Maturity Model, which centers on asset management and maintenance in line with Industry 4.0 principles and continuous production processes. This model introduces the Lean Smart Maintenance (LSM) philosophy, combining efficiency (lean) and intelligence (smart), along with a corresponding Maturity Model (MM), to steer organizations toward excellence in asset management and maintenance. Reference [120] also considered the lean philosophy in their study, developing a model that integrates Lean, Total Predictive Maintenance (TPM), and enabling technologies of Industry 4.0, applied to conveyor belts that are widely used for continuous bulk material transportation. This model enables real-time monitoring of key maintenance indicators and allows data analysis through free IoT applications.

Reference [63] discussed the changing role of operators in the transition from traditional manufacturing processes to Industry 4.0. In the study conducted by [63], the integration of an advanced system with a finite element method tool enabled the prediction and control of aspects such as microstructural changes and hardness variation in real time, creating an intelligent system capable of making automated decisions, thus transforming the operator's role into that of a supervisor.

Considering that each material has specific characteristics that influence how information is collected and processed, [60] presented a decision support system based on ultrasound data, which can be an effective approach when the rheological properties of a fluid are highly complex. In discrete production processes, the identification (ID) assigned to each unit is typically unique, facilitating the collection and storage of various parameters for intelligent manufacturing applications [58]. However, the continuous nature of production poses challenges in defining the product units or batch numbers. This limitation is addressed using Automatic Virtual Metrology (AVM), which is designed to accurately define each unit or label a product in a continuous production setting [58]. Consequently, technologies such as AVM are increasingly utilized in continuous processes, particularly in online and real-time inspections. As noted in [58], AVM have been implemented across diverse sectors, revolutionizing traditional offline sampling inspection methods by enabling comprehensive online and real-time inspection capabilities [121] classified virtual metrology (VM) as one of the most important enabling technologies in smart manufacturing. Because it can replace physical measurements, it is particularly useful when inspection is impractical, owing to cost or safety concerns. This article [121] presents the development of a virtual metrology system for smart manufacturing, focusing on a case study of spandex fibers.

Focusing on continuous production protection, [64] the current level of automation technology development for continuous production is discussed, considering the requirements of the fourth industrial revolution, Industry 4.0. In this study, the authors proposed a new classification of industrial process safety levels, considering the steps for identifying and eliminating emergency situations.

Reference [122] analyzed 29 production plants of the same continuous process company to identify the relationship between different maintenance practices and productive efficiency in continuous process plants, as well as the moderating effect of good training practices. As a result, [122] it was found that there is a demand for Industry 4.0, through the introduction of skill improvement programs and the requalification of the workforce.

Reference [2] developed a real-time early warning system for smart and sustainable plastic film manufacturing. They also devised real-time preventive measures for a challenging-to-automate crushing process by employing a Flexible Structure Production Control (FSPC) method that is deemed essential for the implementation of Industry 4.0.

-Context 2 – Industry 4.0 in continuous production processes in the mining industry: Data and predictive engineering are essential pillars for future smart production implementation. Reference [80] developed and implemented performance indicators for aggregate production by using dynamic simulations. The utilization of dynamic simulation platforms and data acquisition systems can equally be considered as supportive tools for adapting Industry 4.0, in the aggregate production industry. In addition, focusing on prediction, [106] proposed a predictive control model based on a neural network for a paste thickener on an industrial Internet platform. The results were promising and suggested that modern architectures for neural networks already in use in other areas could be attractive for process control.

Reference [118] used surface scanning technology to send 3D scanner data to a data center, operator, and electrical cabinet. The received data allowed for the creation of a 3D model of the oversized upper surface with linear dimensions, and consequently positioning the hydraulic hammer tool over the oversized surface and crushing it with high-power strikes. Typically, the hydraulic hammer operation requires operator intervention to control the process. The modernization proposal added position control sensor technology to the hydraulic cylinders.

Multiple regression analyses were conducted to forecast the extraction efficiency of industrial IoT in the mining industry [107]. This system enables efficient real-time tracking, and provides crucial information for enhanced control and predictive services.

Reference [112] utilized artificial intelligence for enhanced flotation monitoring in the mining industry and proposed a new approach based on a Convolutional Long Short-Term Memory (ConvLSTM) neural network for the real-time monitoring of chemical composition grades in flotation froth.

Reference [115] conducted a study on the ore crushing process at the Agnico Eagle's Laronde mine to achieve prediction and energy management in a wireless sensor network using kinetic energy harvesting in Industry 4.0. Reference [123] conducted a study on digital twins applied to the advanced monitoring and supervision of the froth flotation process in mineral processing. This study utilized industrial data and simulations based on Artificial Neural Networks (ANNs) to create a precise digital model of flotation cells. Industrial evaluations demonstrated that the model achieved 94% accuracy in estimating flotation cell operations with a response time of only 2 s. These findings underscore the potential of digital twins to enhance process control and industrial efficiency, emphasizing the importance of innovation and improvement in industrial contexts.

Finally, [111] presented machine learning techniques for predicting the remaining useful life using diagnostic data, illustrated with a case study of a jaw crusher. The relevance of machine-learning models in predicting the health status of components was demonstrated by achieving high accuracy.

Fig. 10 presents a graphic summary of the main themes highlighted in the articles on the principle of technical assistance, Industry 4.0, in continuous production processes in the mining industry.

FIGURE 10. Graphic summary of the main themes highlighted in the articles - Context 2 - Principle of technical assistance - Industry 4.0 in continuous production processes in the mining industry.

c: DECENTRALIZED DECISIONS

Context 1 - Industry 4.0 in continuous production processes: The combination of interconnected and decentralized decision-makers allows the simultaneous use of local and global information to improve decision-making and increase overall productivity. Architectures such as the advanced manufacturing cloud of things (AMCoT) and Supervisory Control and Data Acquisition (SCADA) can be used as resources to meet this principle. AMCoT contains factories and clouds [58].

Processes and production lines are decentralized worldwide. An approach called ''Go to Manufacturing Mobility'' (Go2M), based on lessons learned, assists managers in identifying priorities for mobile technology development in continuous process industries. The authors concluded that mobility strategies are crucial to fully explore the decentralization of continuous manufacturing following the advent of Industry 4.0 [61].

Holonic Production Unit (HPU) architecture is an innovative approach for managing continuous production processes [27]. HPUs can detect environmental events, evaluate various courses of action, and adjust parameters according to their missions. The Holonic Manufacturing System (HMS) is designed to configure and reconfigure physical processes as a result of scheduling activities and supervisory tasks to ensure that the established goals of the Water Supply System (WSS) are achieved [27]. HMS seeks to decentralize manufacturing tasks into individual decision-making entities (i.e., holons) to demonstrate autonomous, cooperative, and responsive behavior in manufacturing operations [27]. However, the construction and validation of compatible behavior models for each functional unit present significant challenges [27].

Advanced models enhance decentralized decision-making in terms of quality. For example, a novel reinforcement learning framework and self-prediction artificial neural network model for online process parameter optimization using offline data have been developed for injection molding [105]. This online decision model combines a self-prediction quality model and highlights the role of artificial intelligence in decentralized manufacturing environments [105].

Reference [109] presented an algorithm for surface and single-point quality assessments in continuous production by using a 3D laser Doppler scanning vibrometry system. This system performs fast, non-contact measurements in milliseconds, comparing the modal responses of products with an ideal model and storing data in the cloud. This technology is ideal for quality management in Industry 4.0, enabling quality assessments in production lines without additional stops and human involvement synchronized with the production flow.

Context 2 – Industry 4.0 in continuous production processes in the mining industry: In terms of the principle of decentralized decision-making in the continuous processes of the mining industry, three studies were identified that address the topic, as follows.

Reference [112] conducted a demonstration of a cyber-physical system for automated conveyor belt operation to control the inventory across multiple stocks (laboratory scale). They explored a cyber-physical system (CPS) proposal that utilizes an optimization technique to minimize the deviation of the live inventory from its target values using an autonomously controlled tripper car on a conveyor belt. This system can be regarded as an autopilot or a self-directed process, known as an expert system.

Reference [124] investigated the use of an online analyzer to replace conventional sampling and laboratory analysis methods, enabling real-time detection of concentration levels in differential flotation processes. This system leverages hybrid feature extraction (HFE) and machine learning, increasing efficiency and providing instant supervision of the flotation circuit. It automates tasks, allowing operators to monitor flotation foam directly from control rooms, eliminating the need for complex and expensive X-ray-based systems, and ensuring an optimal polymetallic flotation performance.

However, implementing decentralized decisions is challenging. As noted by [125], ''In the process of adjusting the system software, it was revealed that it was impossible to remotely control the hydraulic unit to rebuild the gap in automatic mode due to failures in the adjustment of the sensors of the hydraulic unit pressure switch.'' This highlights the technical difficulties that can arise in decentralizing control systems. **Fig. 11** presents a graphic summary of the main themes highlighted in the articles on the principle of decentralized decisions, Industry 4.0, in continuous production processes in the mining industry.

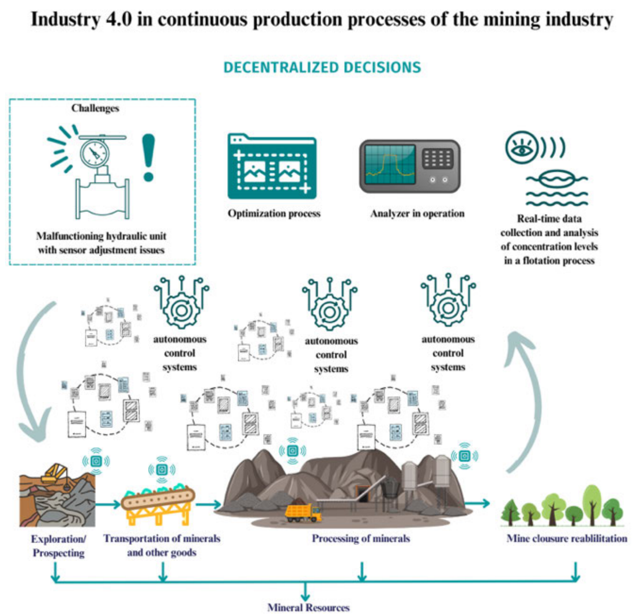

FIGURE 11. **Graphic summary of the main themes highlighted in the articles - Context 2 - Principle of decentralized decisions - Industry 4.0 in continuous production processes in the mining industry.**

d: INFORMATION TRANSPARENCY

Context 1 - Industry 4.0 in continuous production processes: Information transparency is a prerequisite for effective decision-making. In [58], Automatic Virtual Metrology

(AVM) technology was used to achieve fully online and real-time inspections in continuous processes.

In the study [121], titled "Development of a Virtual Metrology System for Smart Manufacturing," the authors present a case study on spandex fiber production, where the virtual metrology (VM) model was integrated into a quality management system. The viscosity of the doped polymer was monitored virtually every 10 min, allowing operators to assess the quality of the final product in real time, a process that had previously taken at least 4 h.

Reference [117] proposed an IoT-based platform for data acquisition and availability in a continuous process manufacturing plant. This platform integrates data from mobile devices and ERP systems, and analyzes them using machine learning and artificial intelligence technologies to visualize key performance indicators (KPIs). These KPIs can be displayed at both factory level and headquarters on static and mobile devices. This platform enables the acquisition, analysis, and provision of data to various devices, thus promoting transparency. Initially implemented in the cement industry, this model can be extended to other sectors and developed in the cloud, offering a Service (PaaS) to customers.

Context 2 – Industry 4.0 in continuous production processes in the mining industry: Reference [107] conducted online monitoring of key data attributes in the mining industry during zinc and lead extraction, utilizing the Industrial Internet of Things (IIoT). The SCADA platform used for this task demonstrates significant flexibility in accumulating data more effectively by employing cloud storage, trend analysis, and front-end utilities. Data analysis was conducted on stored data that could be accessed or controlled through a user interface with back-end coding. Complete process visualization was achieved via SCADA using the PLC AC500 interface and a network of multisensor nodes incorporating Ethernet, enabling operation and monitoring even in remote locations, thus promoting information transparency.

A real-time graphical user interface (GUI) was developed [124]. This GUI enables operators to monitor the flotation process and assess the mineral content directly from their control rooms, thereby providing immediate insights and facilitating quick decisions. The interface enhances flotation monitoring by combining human expertise with automated system intelligence.

Reference [125] proposed the structure of a Crushing and Screening Digital System (CSDS), that was successfully implemented in a cone crusher. This system enables the continuous monitoring of equipment during operation and regulation of crusher productivity. Additionally, it integrates technological units for efficient information exchange and notifies the operator in case of failure by utilizing the SCADA system. The SCADA electronically records all operational data. The CSDS significantly improves operator comfort by providing a unique interface for crusher control and access to additional information.

Fig. 12 presents a graphic summary of the main themes highlighted in the articles on the principle of information transparency, Industry 4.0, in continuous production processes in the mining industry.

e: SUSTAINABILITY

Context 1 - Industry 4.0 in continuous production processes: According to [64], assessing industrial safety at all stages of the continuous production lifecycle is essential for informed decision-making, reducing environmental damage, and improving overall safety. This study discusses the development of automation technologies in continuous production aligned with Industry 4.0 and proposes a classification of industrial safety levels at various lifecycle stages, emphasizing the importance of sustainability and safety in each phase.

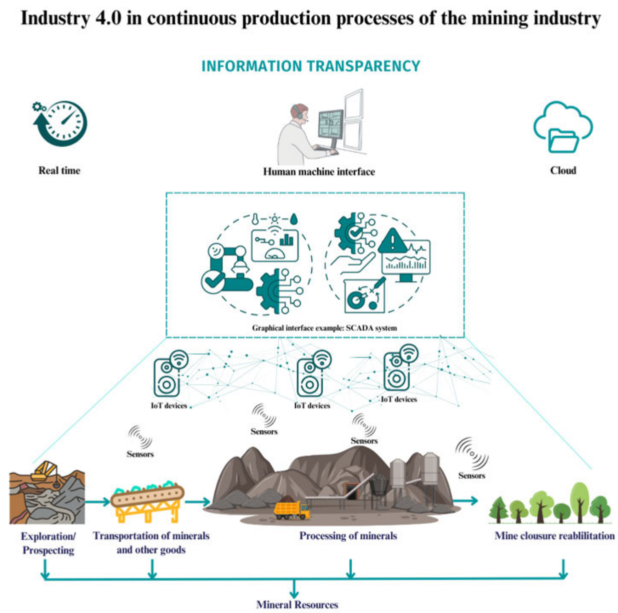

FIGURE 12. **Graphic summary of the main themes highlighted in the articles - Context 2 - Principle of information transparency - Industry 4.0 in continuous production processes in the mining industry.**

Reference [119] highlighted the importance of adopting semi-supervised Machine Learning models such as Convolutional Neural Networks (CNN), autoencoders (AE), and bagged decision trees to establish a more robust reliability model.

A sustainable prediction algorithm was validated using real data and an accuracy of approximately 100% was achieved. The system reduces investment costs and management risks, identifies defects in real-time, and improves sustainability. However, it faces challenges, such as the limitation of application to specific data, lack of comparative studies, and limited understanding of physical properties, necessitating further research to generalize predictive models and automate more semi-automated zones.

The study [63] highlighted that the implementation of Industry 4.0-focused technologies significantly improves process flexibility and manufacturing efficiency, resulting in less waste and increased productivity.

Context 2 – Industry 4.0 in continuous production processes in the mining industry: Reference [116] emphasized the advantages of dry stacking filtered tailings as a sustainable and safe alternative to traditional tailing storage facilities. This study suggests that this method, paired with Industry 4.0, can enhance the operational efficiency, cut costs, and mitigate the environmental impacts of mining waste management. Technologies such as the Internet of Things (IoT), advanced data analytics, Machine Learning (ML)/ artificial intelligence (AI), Digital Twins (DT), integrated engineering, intelligent sensing, and communication have been highlighted as enablers of this approach.

Reference [111] developed a method to ensure the energy autonomy of a Wireless Sensor Network (WSN) using piezoelectric technologies to harvest kinetic energy. They focused on the entire network rather than a single sensor, which is essential for controlling complex industrial processes. Vibration measurements were performed at 12 locations and a model was created to evaluate the power harvested by each sensor. They proposed a power-harvesting predictor from vibrations (PHPV) that significantly improved the prediction accuracy compared to previous predictors. Additionally, they introduced a hierarchical energy-balancing protocol (HEBP) to maximize communication between sensors, allowing up to 100% of them to communicate, compared with 66% of previous protocols.

Reference [124] conducted a study that focused on real-time determination of mineral grades in flotation froths using Deep Learning. Their approach integrates image processing techniques and deep learning models, leveraging data collected from a flotation plant in Guemassa, Morocco. Achieving a prediction accuracy of up to 0.94 for mineral composition, their proposed online analyzer enhances the process control efficiency and accuracy, surpassing traditional methods and X-ray-based commercial systems. This system allows real-time detection and operator supervision, with future enhancements potentially incorporating additional variables such as pH and density, to further refine and possibly replace conventional laboratory techniques. This system allows real-time detection and direct operator supervision, contributing to operational efficiency and sustainability in the mining sector.

Reference [114] conducted a study to identify how Industry 4.0 digital technologies can improve coal mining sustainability. They compared two processing plants in Latin America: one with the 1980s technology and the other with updated facilities from 2018. The implementation of Industry 4.0 technologies reduced variability in quality parameters, water and energy consumption, waste generation, and harmful emissions. However, these technologies did not significantly reduce the number of accidents but decreased the risks for operators and reduced the total number of jobs. The conclusions suggest that the technologies helped achieve environmental and economic improvements and highlight the need for further studies to explore their social benefits and impacts on neighboring communities.

Reference [32] highlighted that contemporary mining incorporates concepts aimed at building a more sustainable and efficient industry, reducing environmental footprints, and enhancing the safety of mining operations.

Fig. 13 presents a graphic summary of the main themes highlighted in the articles on the principle of sustainability, Industry 4.0, in continuous production processes in the mining industry.

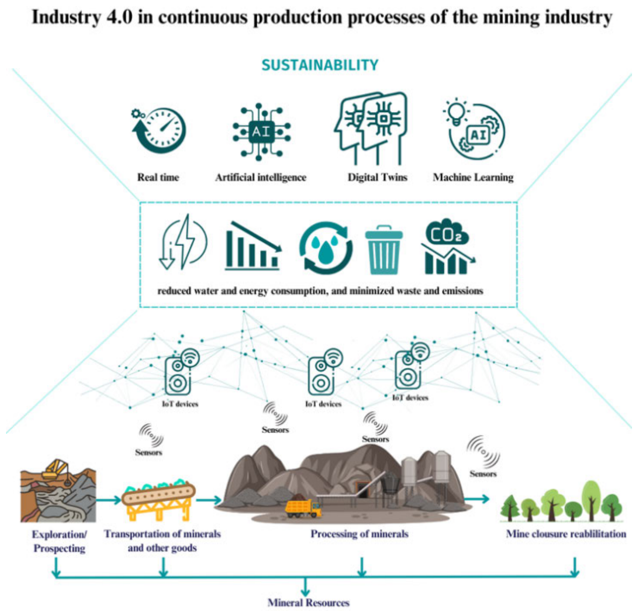

FIGURE 13. Graphic summary of the main themes highlighted in the articles - Context 2 - Principle of sustainability - Industry 4.0 in continuous production processes in the mining industry.

2) TYPICAL RESOURCES AND ENABLING TECHNIQUES – CONTEXT 1 AND 2

The typical resources and enabling techniques identified in the qualitative analysis of the articles selected from the systematic review are presented in **Tab. 13**. These findings were crucial in identifying the implementation patterns of Industry 4.0, in the two analyzed contexts: Context 1, which focuses on Industry 4.0, in continuous processes in general, and Context 2, which concentrates specifically on continuous production processes in the mining industry. These contributions are essential for developing the framework, as they help identify challenges and facilitators, providing a solid foundation for constructing a robust conceptual model applicable to continuous mining operations within the Industry 4.0 paradigm.

a: ADVANCED MANUFACTURING CLOUD OF THINGS (AMCOT)

Context 1 - Industry 4.0 in continuous production processes
Reference [58] introduced AMCoT as a platform to achieve Industry 4.0 objectives and reached the zero-defect goal by applying

TABLE 13. Typical resources and enabling techniques – Context 1 and 2.

Typical resources and/or important enabling techniques focus on Industry 4.0 (continuous processes)	Design Principle									
	Interconnection		Decentralized decisions		Technical assistance		Transparency of information		Sustainability	
	Context 1	Context 2	Context 1	Context 2	Context 1	Context 2	Context 1	Context 2	Context 1	Context 2
Advanced Manufacturing Cloud of Things (AMCoT)			[58]		[58]		[58]			
Artificial intelligence (AI)/ Machine Learning (ML)/ Deep Learning (DL)	[24]		[24], [105]	[112] ,[124]	[24], [63], [119]	[106], [112], [115], [112], [113]		[124]	[63], [119]	[116], [124]
Augmented Reality		[32]	[61]		[61]					
Automatic Virtual Metrology (AVM)			[58], [109]		[58], [121]		[58], [121]			
Big Data Analytics (BDA)	[24], [108]		[24]							[114]
Camera	[115]	[118]	[61], [109]		[61], [109]	[118], [115]		[115]		
Cyber-Physical Systems (CPS)	[76]		[61]	[112]		[112]				
Cloud computing (CC)	[114]		[58]							[114]
Crushing and Screening Digital System (CSDS)				[125]				[125]		
Digital twins	[108]		[61]		[26], [80]	[123]		[123], [116]		[116]
Dynamic simulation	[108]				[80]	[80]				[116]
Flexible structure production control (FSPC)	[2]				[2]				[2]	
Holonic Production Unit (HPU)			[27]							
Internet of Things (IoT)/ Industrial Internet of Things (IIoT)	[63], [117], [108]	[107], [114]			[60], [63], [120]	[106], [107]	[117]	[107]	[63]	[116],[114]
Industrial control systems/ Supervisory Control and Data Acquisition (SCADA) systems	[76]	[107]		[125]		[107]		[107], [125]		
3D technology		[118]	[109]		[109]	[118]				
Smart sensors	[26], [60], [76]									
System's real-time graphical user interface (GUI)			[61]	[124]		[115]	[61], [76]	[115], [124]		[124]
Human participation and high - level workforce qualification					[76], [122]	[118]				

Automatic Virtual Metrology (AVM) technology. Developed based on the Internet of Things (IoT), Cloud Computing (CC), Big Data Analytics (BDA), and Cyber-Physical Systems (CPS) [58].

b: ARTIFICIAL INTELLIGENCE (AI)/MACHINE LEARNING (ML)/DEEP LEARNING (DL)

Context 1 - Industry 4.0 in continuous production processes: Reference [119] utilized Machine Learning (ML) to make informed decisions regarding maintenance and production in a petrochemical process. The use of ML models enabled the early identification of process variables when analyzed together, indicating that the critical equipment was prone to failure. Reference [24] also adopted machine-learning solutions to enhance the efficiency and competitiveness of continuous processes in oil refineries. Reference [63] implemented AI software algorithms to gather and analyze data, provide automated choices, and minimize human intervention in continuous industrial wire manufacturing. In [105], an artificial neural network model for self-prediction was used to dynamically optimize an ultra-high-precision product process in continuous injection molding (IM).

Context 2 - Industry 4.0 in continuous production processes in the mining industry: Reference [106] used a model predictive control scheme based on neural networks (NNMPC) to control an industrial thickener. The architecture and methodology proved effective in controlling real industrial processes using state-of-the-art artificial intelligence techniques implemented with open-source tools. Similarly, [116] discussed how AI and ML are part of a new paradigm for mine waste management. Reference [124] employed supervised Machine Learning algorithms (ML), artificial neural networks (ANN), and convolutional neural networks (CNN) to control the froth flotation process in the mineral industry, which is challenging because of its multiple impacting parameters. To predict the mineral concentrate grades, image processing algorithms were used with features extracted from the flotation froth, including the texture, bubble size, velocity, and color distribution. Similarly, [115] investigated the application of artificial intelligence for enhanced flotation monitoring in the mining industry, proposing Convolutional Long Short-Term Memory (ConvLSTM) neural networks to process video frames of the froth and extract sequential characteristics. In [112], a real-time deep neural network was applied to assess the level of chickpea seeds (equivalent in size to crushed ore particles) in the containers. Reference [112] used OpenCV as a machine-learning (ML) tool to provide an optimized real-time computer vision library. Reference [119] applied Machine Learning techniques to predict the Remaining Useful Life (RUL) using diagnostic data in a Jaw Crusher. The data were preprocessed to facilitate the evaluation of four regression machine learning models: Bayesian Linear Regression, Poisson Regression, Neural Network Regression, and Random Forest.

c: AUTOMATIC VIRTUAL METROLOGY (AVM)

Context 1 - Industry 4.0 in continuous production processes: AVM has been applied across various sectors to transform offline sampling inspection with metrological delay into total online and real-time inspection [58]. In [58], an example of an AVM application was presented for Carbon Fiber Manufacturing and [121]spandex fiber production.

d: AUGMENTED REALITY

Context 1 - Industry 4.0 in continuous production processes: Reference [61] presents an approach to incorporating mobility in continuous manufacturing after the advent of Industry 4.0. Augmented reality is highlighted as a potential alternative for quality inspection and fluidity control.

*Context 2 – Industry 4.0 in continuous production processes in the mining industry:*According to [32], technologies such as augmented and virtual reality, along with digital twins, have the potential to enhance the design and construction of mining projects as well as optimize extraction and processing operations, although the article does not provide specific examples of their use.

e: BIG DATA ANALYTICS (BDA)

Context 1 - Industry 4.0 in continuous production processes: In [24], Big Data solutions were employed to enhance the efficiency and competitiveness of continuous processes such as oil and gas downstream. Reference [108] commented that BDA is a typical resource and/or enabling technique that is important for the optimized management of chemical plant operations guided by Industry 4.0.

Context 2 – Industry 4.0 in continuous production processes in the mining industry: In [114], BDA is presented as an Industry 4.0 technology focusing on sustainability in the coal mining industry. This provides sophisticated models that enable sales forecasting, quality control, and supply chain integration, thereby contributing to reduced inventory, transportation costs, and energy savings.

f: CAMERA

Context 1 - Industry 4.0 in continuous production processes: In [61], the tablet camera is one of the resources used as a data input device within a mobile service. This allows actors (such as operators or technicians) to capture visual information directly in the workplace. In summary, the camera is used to collect visual data that complement other sensor inputs, providing a more comprehensive and accurate view of the work environment, empowering actors, and facilitating real-time decision-making. In [109], a camera was used in quality control and assurance processes to capture images that enhance data analysis, perform quick and precise visual inspections, and complement other optical methods of non-destructive testing. This facilitates fault detection and quality assessment, supporting the efficiency of quality management in Industry 4.0.

Context 2 – Industry 4.0 in continuous production processes in the mining industry: Reference [118] highlights the importance of a high-resolution multi-view camera for remotely operating all the necessary work for tool installation and large-sized mineral crushing. Reference [115] used a GigE camera connected to an NVIDIA Jetson Nano, which processes camera frames in real time, to deploy an online analyzer at the flotation process site in the mineral industry.

g: CLOUD COMPUTING (CC)

Context 1 - Industry 4.0 in continuous production processes: In [58], the cloud plays a crucial role by storing vast amounts of data generated during production, which are processed using big data tools such as the Hadoop Distributed File System (HDFS) for efficient management. This allows real-time inspection and decision-making, overcoming the challenges of managing large datasets and the physical distance between the factory and data center. The cloud also facilitates the future integration of additional intelligent services, enhancing overall quality and efficiency in line with the objectives of Industry 4.0.

Context 2 – Industry 4.0 in continuous production processes in the mining industry: According to [114], CC facilitates product lifecycle monitoring. It connects all stakeholders, including customers, allowing for the comprehensive management of the entire product lifecycle and supporting sustainability in the coal mining industry (including continuous processes).

h: CYBER-PHYSICAL SYSTEMS (CPS)

Context 1 - Industry 4.0 in continuous production processes: [76] provided a detailed explanation regarding the distribution of IoT/IIoT/CPS technology across networks, considering the types of interaction. In summary, Cyber-Physical Systems (CPSs) are defined as the integration of sensors, embedded computing, and networks into physical objects with feedback loops to monitor and control nearby physical environments in a collaborative and Internet-connected manner. Reference [61] explain that cyber-physical elements (whether employees or machines) represent the team dimension of the mobility strategy in continuous manufacturing, supporting the implementation of the mobile digitalization required by Industry 4.0.

Context 2 – Industry 4.0 in continuous production processes in the mining industry: Reference [112] demonstrated a cyber-physical system (CPS) in the mining industry designed to autonomously manage the handling of solid materials flowing on a conveyor belt, segregating them into distinct stockpiles.

i: DIGITAL TWINS (DT)

Context 1 - Industry 4.0 in continuous production processes: Reference [26] presented a theoretical framework for modeling and simulating processes in the context of Digital Twins for continuous industrial systems. The models developed typically have offline use and can be employed in online Digital Twins alongside the physical system with the aim of monitoring, root cause analysis, constraint handling, performance optimization, and system behavior recovery [26]. Reference [108] commented that the digital twin is part of the typical resources and/or enabling techniques important for the optimized management of chemical plant operations guided by Industry 4.0. Reference [61] also introduced Digital Twins as a high-potential contribution to task fluidity for integrating mobility into continuous manufacturing. As highlighted by [26] and identified in the reviews conducted by the authors of this article, there are a limited number of studies in the literature on the process modeling and simulation of continuous systems in the context of Digital Twins.

Context 2 – Industry 4.0 in continuous production processes in the mining industry: Reference [116] highlights the importance of Digital Twins in simulating processes within the new paradigm of mine waste management. Reference [123] discussed the use of DT to monitor and supervise froth flotation during mineral processing.

j: 3D TECHNOLOGY

Context 1 - Industry 4.0 in continuous production processes: Reference [109] introduces a 3D Laser Vibrometry System as a potential solution to reduce the time required for single-point and surface quality assessment in continuous production based on the Industry 4.0 concept. This single-point measurement requires only a few milliseconds and can be synchronized with the production process flow [109].

Context 2 – Industry 4.0 in continuous production processes in the mining industry: The study in [118] utilized 3D scanner technology for surface scanning as a solution in mineral processing, specifically to measure large surface dimensions and positions within the crusher throat.

k: FLEXIBLE STRUCTURE PRODUCTION CONTROL (FSPC)

Context 1 - Industry 4.0 in continuous production processes: Reference [2] developed a real-time early warning system for film production processes that cannot be fully automated owing to the inability to install sensors. Using the Flexible Structure Production Control (FSPC) method, semi-automated processes are integrated with automated systems to predict and detect failures. A predictive algorithm was created and validated using real data to achieve a high accuracy. Despite the challenges in generalizing to other contexts, this study proposes a new paradigm for manufacturing, suggesting greater flexibility and cost reduction in complex processes while highlighting the need for further research to automate semi-automated areas.

l: INTERNET OF THINGS (IOT)/INDUSTRIAL INTERNET OF THINGS (IIOT)

Context 1 - Industry 4.0 in continuous production processes: IoT is part of the typical resources and enabling technologies important for the optimized management of chemical plant operations guided by Industry 4.0 [108]. Reference [63] equipped a continuous industrial wire-manufacturing plant with IoT to connect humans and technologies. Reference [117] proposed an IoT-based model platform to acquire various data generated (mobile devices and ERP systems) in a continuous process manufacturing plant, specifically cement manufacturing. Reference [117] highlighted that integrating the existing Industrial Internet of Things (IIoT) with mobile devices while meeting security requirements is a challenge identified by continuous process manufacturing organizations [63]. In [120] a free Internet of Things (IoT) application, Thing Speak was utilized to collect the downtime and cycle time data of conveyor belts (ECs), which are widely used in the continuous transport of bulk materials. These data were sent to the cloud, where they were stored, processed, and analyzed.

Context 2 – Industry 4.0 in continuous production processes in the mining industry: Reference [116] discusses how the IoT is part of a new paradigm in mine waste management, where machines, equipment, and various mining operation artifacts communicate with each other. In [106] the Industrial Internet of Things (IIoT) platform is utilized to address regulatory control issues in mineral processing equipment. Reference [107] employed IoT-based monitoring and data acquisition to evaluate the recovery of zinc contained in zinc sulfide leach liquor during continuous operation, offering real-time tracking efficiency and crucial information for improved control and forecasting. The IoT is also presented as a tool to help reduce waste generation and landfill disposal.

m: SMART SENSOR

Context 1 - Industry 4.0 in continuous production processes: Reference [60] utilized data-driven soft ultrasonic sensors for online monitoring and control of rheological properties, measuring the quality of a complex mixture during a continuous process. In [26], the parameter values were continuously monitored using appropriate sensors in all the units of a continuous industrial process. In [76], for the continuous steel manufacturing process, temperature sensors monitored the steel in the mold to prevent manufacturing issues, whereas the SCADA system adjusted the parameters in real-time to maintain efficiency and stability.

*Context 2 – Industry 4.0 in continuous production processes in the mining industry:*Sensors are the foundation of virtual simulation and are part of the new paradigm in waste management in mining [116]. Reference [118] used light-barrier technology for online detection of large-dimension materials using detection sensors in mineral processing. Reference [111] proposed a solution to better manage the energy of an entire wireless sensor network (WSN) for the vibration measurements of an ore crushing mill in a mine. Reference [113] used smart sensors as an integral part of predicting the remaining useful life using diagnostic data from a jaw crusher.

n: INDUSTRIAL CONTROL SYSTEMS/SUPERVISORY CONTROL AND DATA ACQUISITION (SCADA) SYSTEMS

Context 1 - Industry 4.0 in continuous production processes Reference [76] provides a comprehensive view of Supervisory Control And Data Acquisition (SCADA) systems in continuous process control, focusing on the steel industry. Reference [76] SCADA primarily refers to the concept and process of supervisory control over an industrial process, as well as collecting and analyzing related data, rather than being tied to specific hardware or software.

Context 2 – Industry 4.0 in continuous production processes in the mining industry: Reference [125] The SCADA system was used at the operator station, where a visualization project was implemented to monitor the condition of the crusher equipment. In [107], the SCADA interface, developed for zinc and lead extraction in continuous operations within the mining industry with IoT, confirmed the flexibility of accumulating data in a more enhanced manner using cloud storage, trend analysis, and front-end interface utilities.

o: HOLONIC PRODUCTION UNIT (HPU)

Context 1 - Industry 4.0 in continuous production processes: Reference [27] proposes an architecture of the Holonic Production Unit (HPU) as a solution to control continuous production processes. This innovation focuses on continuous processes, where each mode of operation is discrete and the global dynamics involve transitions between these states. The behavior of a production unit is described as a hybrid dynamic system with monitoring mechanisms. Each discrete state has its own control law to maintain or achieve a target state, with constraints on the inputs and outputs. Implementing distributed systems requires geographically distributed control equipment, high-speed connections, and capability to handle failures. In [27], to implement the Holonic Production Unit (HPU) architecture for continuous production processes based on Industry 4.0, it was necessary to integrate the traditional architecture based on (Programmable Logic Controller (PLC) and its SCADA (Supervisory Control and Data Acquisition (SCADA). The benefits of decentralized decisions in continuous production, according to [27], include i) automatic evaluation of potential system configurations; ii) supervisor holes generating operation sequences for configuration changes, with each mode of operation represented as a discrete state; and iii) improved predictive behavior for systems such as the Water Supply System (WSS) under various operational conditions [27].

p: SYSTEM'S REAL-TIME GRAPHICAL USER INTERFACE (GUI)

Context 1 - Industry 4.0 in continuous production processes: Despite challenges related to situational awareness and operator competence, the GUI is a solution for obtaining an overview of the production line in the continuous steel manufacturing process [76]. Reference [61] highlighted the importance of tablets and smartphones in improving the quality of information compared with the use of non-mobile hardware.

Context 2 – Industry 4.0 in continuous production processes in the mining industry: In [115] and [124], human experts used the real-time GUI of the system to monitor the flotation process and assess the predicted mineral concentrations. This interface provides immediate insights, enabling timely decisions and enhancing the efficiency of the flotation monitoring. This collaboration combines human expertise with machine intelligence to optimize flotation operations.

q: HUMAN PARTICIPATION AND HIGH-LEVEL WORKFORCE QUALIFICATION

Context 1 - Industry 4.0 in continuous production processes: Reference [122] investigated how best maintenance practices impact Overall Equipment Effectiveness (OEE) in continuous industries such as chemicals, beverages, steel, and glass. Effective management enhances reliability and availability and reduces costs. The authors emphasize that training is crucial for maximizing results, especially in Industry 4.0. Similarly, [76]the increasing complexity of SCADA and GUI human–machine interface (HMI) systems requires more skilled operators, but insufficient training hinders their performance. It is essential to develop methods that enhance situational awareness of operators and render SCADA systems more flexible and adaptable.

Context 2 – Industry 4.0 in continuous production processes in the mining industry: With the COVID-19 pandemic and Industry 4.0 revolution, human involvement needs to be minimized in uninterrupted production lines to avoid stoppages [118]. The authors proposed a solution for automating mining processes by assigning all the "dirty" work to robots, making humans the key element in the creation process, responsible for developing and operating new technologies, and sometimes handling maintenance and repair tasks.

r: DYNAMIC SIMULATION

Context 1 - Industry 4.0 in continuous production processes: Reference [108] discusses the importance of real-time optimization (RTO) by presenting an algorithm that implements a preliminary scheduling procedure in continuous processes to assist plant operators in making the most strategic decisions for supply chain management, supported by process automation, digitalization, and simulation. As explained in [108], RTO involves typical and/or significant enabling capabilities such as process simulation, digital twins, optimization, IoT, and industrial big data analytics.

Context 2 – Industry 4.0 in continuous production processes in the mining industry: Reference [116] emphasizes the importance of data collected by sensors for the virtual simulation of processes as part of the new paradigm in mine waste management. The use of a dynamic simulation platform and data acquisition systems can equally be considered a supporting tool for adapting Industry 4.0 in the aggregate production industry, where processes are conducted as continuous operations, in contrast to discrete operations [80].

s: CRUSHING AND SCREENING DIGITAL SYSTEM (CSDS)

Context 2 – Industry 4.0 in continuous production processes in the mining industry: Reference [125] proposed a CSDS structure that enables the integration of a set of interconnected technological units (crushing and screening production), providing the operator with a single interface to control various technological units.

C. R.Q.3: WHAT ARE THE MAIN TOPICS OF INTEREST IN THE STUDIES RELATED TO CONTEXTS 1 AND 2?

The Word Cloud graphs for each of the contexts (**Fig. 14 (a)** and **Fig. 14 (b)**) support these findings, highlighting that Industry 4.0 and continuous processes are central themes across both contexts. In particular, context 1 emphasizes terms such as machine learning, artificial intelligence, and data analytics, reflecting a focus on leveraging advanced technologies for smart manufacturing and process control. Context 2 prominently features terms such as deep learning, mineral processing, and industrial automation, indicating interest in the application of intelligent systems.

automation specifically to mineral extraction and flotation processes.

The content analysis of the articles derived from reading the articles for **R.Q. 1** addressed **R.Q.3**. When evaluating the content discussed in both contexts, it was observed that both developed studies focused on process optimization

(a) (b)

FIGURE 14. (a) Word cloud graph – Context 1 and (b) Word cloud graph – Context 2.

and control (**Fig. 15**). This includes the application of data analysis, artificial intelligence, and automation to optimize production, improve efficiency, and increase the overall effectiveness of the manufacturing processes.

Table 14 demonstrates that the authors also studied equipment maintenance, monitoring, and reliability, highlighting the importance of ensuring the continuous and safe operation of industrial systems.

In addition, inspection, quality, and optimization technologies have been emphasized. These areas are essential for ensuring that final products meet the required quality standards and for proactively identifying and correcting issues in the manufacturing process. Furthermore, there is a growing interest in innovation in manufacturing processes. The authors explored the architectures, models, roadmaps, and theoretical frameworks to understand and implement the principles of Industry 4.0.

Challenges and process safety control are important areas of study. Operational safety is crucial for preventing accidents, protecting workers, and avoiding production disruptions. The authors investigated methods to identify and mitigate risks, ensure a safe working environment, and develop resilient industrial processes.

D. R.Q.4 WHAT ARE THE CHALLENGES RELATED TO CONTEXTS 1 AND 2?

1) CHALLENGES OF LIMITED STUDIES/ APPLICATIONS OF INDUSTRY 4.0 WITH A FOCUS ON CONTINUOUS PROCESSES

Studies often focus on intermittent and discrete processes, with fundamental challenges in continuous processes being relatively neglected compared with batch processes [27], [121]. Reference [27] highlighted the lack of prior studies and applications related to holonic systems in continuous production processes, such as Water Supply Systems (WSS), petroleum refining, and power plants. They argued that such systems can enhance the overall efficiency and responsiveness of the manufacturing operations. For instance, despite extensive literature on virtual metrology (VM), continuous production contexts have received less attention [121]. A recent study from 2023 [26] is noted as the first attempt to introduce a generic step-by-step methodology for building and operating a realistic continuous process model within the Digital Twins context. Reference [61] presented an approach for incorporating mobility in continuous manufac-

TABLE 14. **Main themes of the articles – Context 1 and 2.**

Design principle	Context	Process Optimization and Control	Maintenance, Equipment Monitoring and Reliability	Inspection and Quality technologies	Innovation in Manufacturing Processes (Architecture/ Model/Roadmap Theoretical framework)	Challenges	Industrial safety
Interconnection	Context 1	[60], [76], [108], [117]	[2], [60]	-	[76], [117]	[24], [76]	-
	Context 2	[107], [118]	-	-	-		-
Technical Assistance	Context 1	[26]	[2], [26], [60], [110], [119], [120], [122]	[26], [58], [121], [80],[26], [58], [121]	[26], [63], [120]	-	[64]
	Context 2	[106], [107], [112], [118], [123]	[80], [113]	[80] , [115]	-	-	-
DecentralizedD ecisions	Context 1	[27], [61], [105]	-	[58], [109]	[27], [61], [105]	-	-
	Context 2	[112]	[125]	[124], [125]	-	-	-
Information Transparency	Context 1	[117]	-	[58], [121]	[117]	-	-
	Context 2	[107], [125]	[125]	[124]	-	-	-
Sustainability	Context 1	-	[2], [119]	-	[63]	-	[64]
	Context 2	[111]	-	[124]	-	[114], [116]	[114], [116]

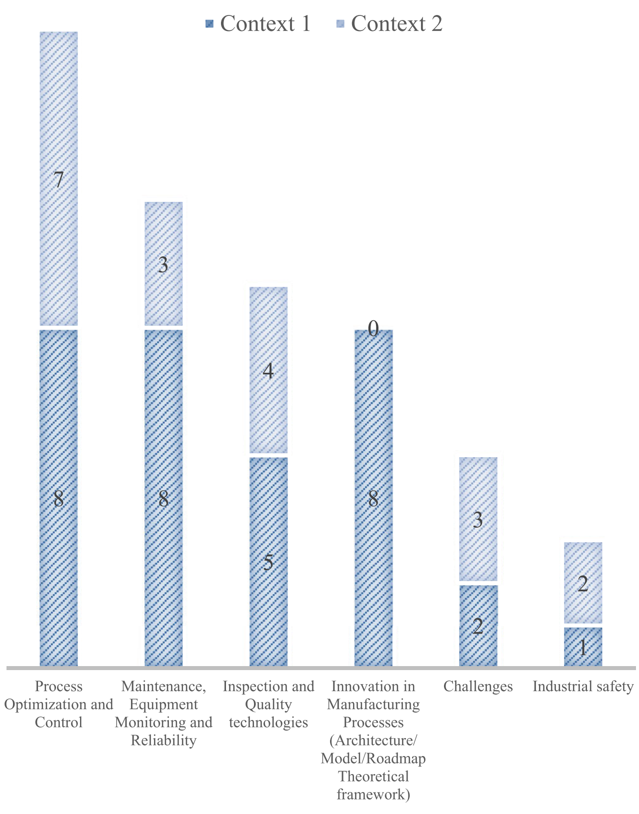

FIGURE 15. **Graphic summary of the main themes highlighted in the articles related to contexts 1 and 2.**

turing following the advent of Industry 4.0 (I.4.0), although this investigation was limited to a single organization, underscoring the need for further studies in other organizations.

2) CHALLENGES RELATING TO THE CHARACTERISTICS OF THE PROCESS

Context 1 - Industry 4.0 in continuous production processes: In industrial settings, particularly in continuous production processes that operate 24 hours a day, seven days a week, any unplanned interruption can lead to significant losses, both in indirect costs and lost profits, potentially reaching millions of dollars per day [76]. When the shutdown is to replace or upgrade an industrial control system (ICS), the new system must justify the downtime and associated costs, which may exceed the cost of the ICS itself [76]. Reference [119] highlighted that the continuous process industry is highly mature, owing to advanced instrumentation and control. According to [121], quality indicators and process data are autocorrelated in the chemical reaction processes. As they depend on previous measurements, recently known values can be used for forecasting. However, as highlighted in [27], continuous production represents a high degree of complexity, wherein a single failure can cause extensive degradation and service interruptions. Reference [119] reported promising results with the proposed method for identifying features that explain anomalies in condition monitoring in continuous processes but also faced limitations, such as identifying false positives. These identifications require validation by maintenance and production engineers, who distinguish between normal and abnormal conditions. Reference [61] pointed out the obvious difficulties in moving the complex equipment used in continuous production. Furthermore, continuous processes present mechanical limitations, as unplanned shutdowns can penalize the plant performance when restarted. To maintain production rates, it is necessary to further increase the operational limits. Consequently, the model must be retrained considering the altered operational conditions, which require additional effort from the engineering team [119].

Context 2 – Industry 4.0 in continuous production processes in the mining industry: In the mining industry, high rates of filtered mining waste production present a significant challenge [116]. Additionally, it indicates the need for further work using multiple conveyor systems to address the quality and ore mixing issues [112]. The physical characteristics of minerals may require specific adaptations in processes; for example, [118] sensors must be protected with steel casings owing to the specific application conditions. Moreover, challenges are associated with disruptive innovations. According to [32], the Continuous Mining System (CMS) was an innovation project developed by Codelco in Chile, aiming to create a continuous material handling system for block and panel caving operations. However, the project was canceled owing to several factors: i) the long time required for process validation, ii) validation of the process can be costly, and iii) the system must be proven under real conditions.

3) CHALLENGES OF INFRASTRUCTURE AND INTEGRATION

• *Context 1 - Industry 4.0 in continuous production processes.* Reference [117] discussed how the COVID-19 pandemic has led to significant changes in continuous production processes. Restrictions on employees and professional movement to factories and offices, as well as limitations on physical meetings, made the flow of information from continuous factories to supervision and management teams crucial for making informed decisions and ensuring smooth operations. However, challenges have arisen in integrating the Industrial Internet of Things (IIoT) with the existing control system infrastructure to meet the security requirements for receiving continuous process data and other operational information. The integration of manufacturing SCADA systems with substation automation systems is critical for real-time energy consumption monitoring, which directly impacts production process quality. This integration is complex because of the differences in systems, network protocols, and interoperability issues among vendors [76]. According to [76], most production facilities associated with continuous and costly industrial processes, such as the steel industry, continue to operate on legacy Industrial Control Systems (ICS), with upgrades typically occurring in microphases as part of regular maintenance cycles. Owing to the high causal correlation between the production areas in the steel industry, strict oversight is essential to ensure continuous material flow and prevent delays, requiring the integration of distributed and centralized functions [76]. Additionally, [112] there is a need for further investigations into time synchronization for image processing and IoT device latency, as well as robot optimization and maneuvering for the proper management of Cyber-Physical Systems (CPS).

• *Context 2 – Industry 4.0 in continuous production processes in the mining industry:* Reference [106] highlights the difficulty of finding adequate computing infrastructure capable of handling complex online optimization problems while maintaining real-time performance and reliability. Continuous monitoring of equipment conditions in crushing and screening complexes is crucial to avoid failures and optimize productivity [125]. Similarly, it is important to obtain periodic samples of processed minerals. Reference [124] presented an online analyzer that demonstrated its potential to revolutionize conventional methodologies associated with periodic sampling and delays related to laboratory analyses.

4) CHALLENGES RELATING TO THE AMOUNT OF DATA COLLECTED

• *Context 1 - Industry 4.0 in continuous production processes:*In continuous production processes, it is challenging to precisely define and label each unit produced, leading to the generation of vast amounts of data during quality inspections [58]. For instance, [58] inspecting the quality of a 60-meter carbon fiber would generate 109,500,000 samples in a batch of 300 spins, making it complex to connect all cause-and-effect data necessary for the Automatic Virtual Metrology (AVM) system to conduct quality inspections aimed at achieving zero defects. Reference [26] noted that despite successfully presenting a theoretical framework for modeling and simulating processes in continuous industrial systems, significant challenges remain in data management and decision-making, especially in interaction with tools from Analytics, Machine Learning, Multi-Criteria Decision-Making, and Optimization. Furthermore, a high dependency on process data may require the selection of a subset of relevant features before model construction, which can enhance the data compatibility and interpretability of the model results [121]. In industrial processes such as steel manufacturing, large volumes of data are generated and processed by SCADA systems.

For effective control, these data must be displayed on a Human-Machine Interface (HMI). However, in production lines such as galvanization, the use of larger and multiple screens can create complex interfaces, challenging the operators' ability to interpret them quickly [76]. Reference [105] stated that although the decision model based on reinforcement learning has advanced the continuous process of Injection Molding (IM), it still faces common challenges, such as the lack of theoretical guarantees of convergence and inefficient data usage owing to the reliance on neural networks as function approximators. Reference [115] recognized the limitations of relying solely on neural network models to address complex challenges.

• *Context 2 – Industry 4.0 in continuous production processes in the mining industry:* In the mining industry, challenges related to data augmentation, froth-level detection, and on-site deployment of tiny Machine Learning [124]. Additionally, [106] it is difficult to develop meaningful process models that can support effective decision-making.

V. DISCUSSION OF RESULTS AND RESEARCH AGENDA

This section addresses research question **R.Q.5**: "What knowledge gaps exist in the current literature on Industry

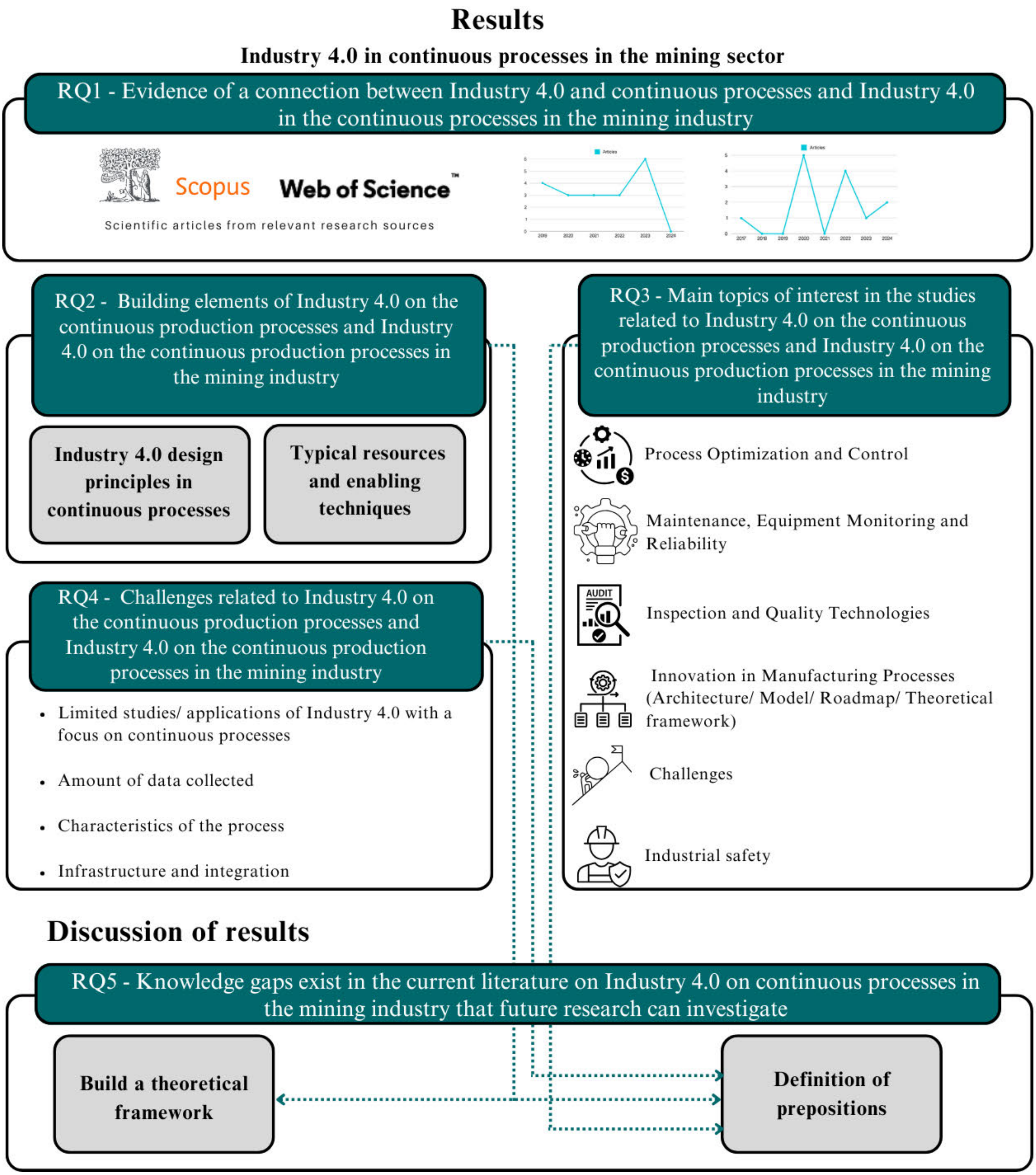

FIGURE 16. Graphic summary of the main themes highlighted in the articles related to contexts 1 and 2.

4.0 in continuous processes in the mining industry that future research can investigate?"

Section A proposes a theoretical framework based on the findings of **R.Q.2**. This framework is designed to highlight the critical areas where Industry 4.0 principles intersect with continuous processes in the mining industry, offering a structured approach to understanding and addressing existing gaps.

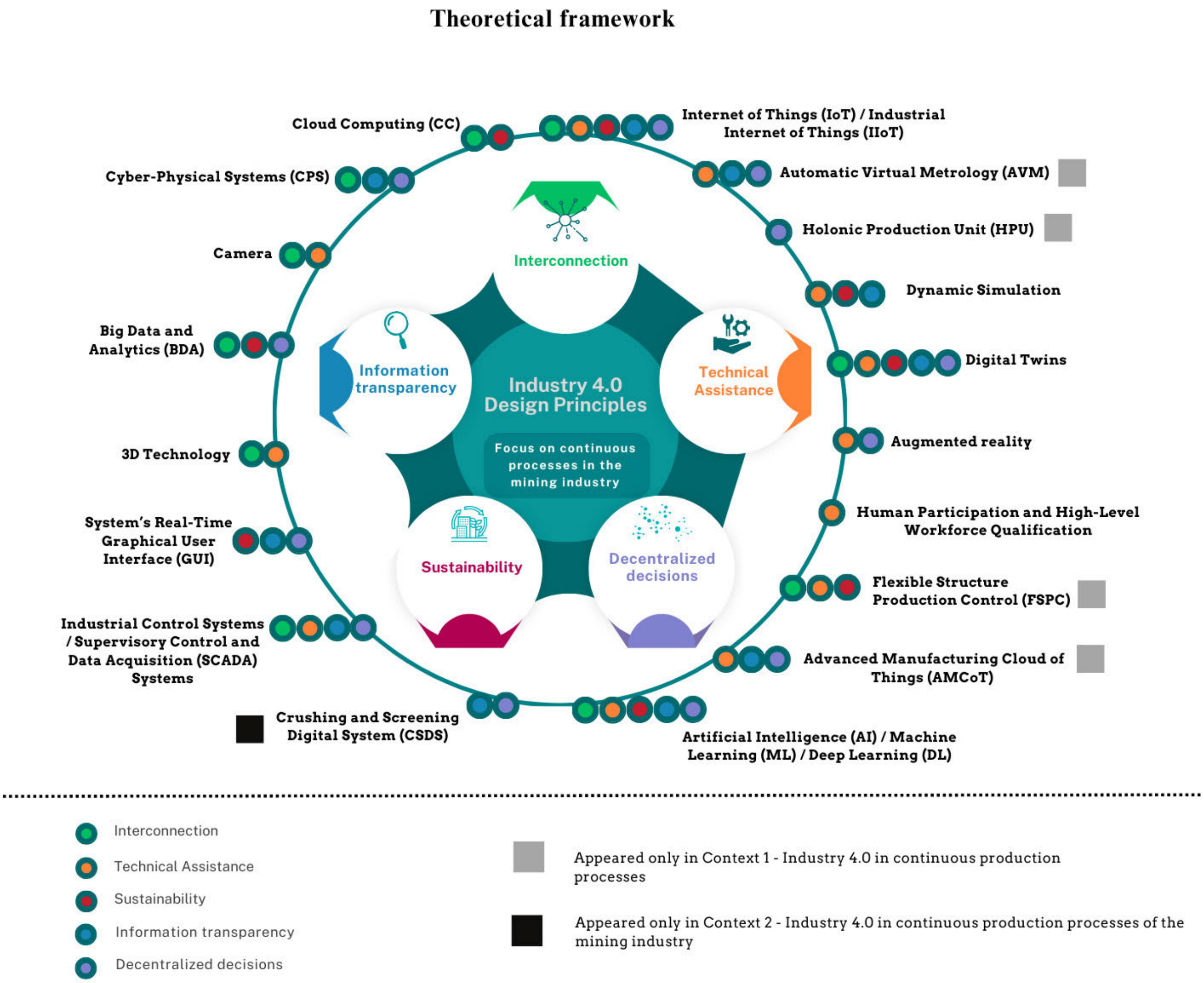

FIGURE 17. **Theoretical framework - Industry 4.0 in continuous production processes and Industry 4.0 in continuous production processes in the mining industry.**

Section B develops propositions based on the results of **R.Q.2**, **R.Q.3**, and **R.Q.4**. These propositions provide valuable insights for future empirical research, guiding the exploration of unexplored aspects of Industry 4.0 in this specific context. **Fig.** 16 illustrates the connection between the results of the previous sections and the outcome of the discussion.

A. THEORETICAL FRAMEWORK

Fig. 17 presents the theoretical framework developed based on the responses obtained for **R.Q.2**. Through a literature review, it was possible to establish a direct correlation between the design principles of Industry 4.0, which focuses on continuous processes, and the typical resources and enabling techniques identified in Contexts 1 and 2.

The primary objective of this study is to contribute specific knowledge regarding continuous production in the mining industry. To achieve this, the research initially aimed to identify opportunities and lessons from Industry 4.0 applicable to continuous processes.

Based on the findings from Contexts 1 and 2, it is possible to develop a theoretical framework that highlights opportunities and lessons that can be adapted and applied to the mining industry. This framework, therefore, offers a structured pathway for the implementation of Industry 4.0 technologies in this sector.

The findings suggest that the mining industry can leverage various learning opportunities that emerge from Context 1 - Industry 4.0 in Continuous Production Processes. These opportunities include the adoption of advanced techniques such as an advanced manufacturing cloud of things, automatic

TABLE 15. Propositions.

Sources of Value Creation	Challenges	Proposition
Interconnection	Integrating legacy control systems in mining with new technologies can be complex and costly. Interconnection increases the cybersecurity attack surface, requiring robust security measures to protect data and operational systems. Operator resistance to new technologies may delay adoption, necessitating effective change management strategies. Additionally, ensuring the scalability of operations and standardizing integration protocols between equipment and systems are critical challenges.	**Proposition 1:** The mining industry can develop robust interconnection infrastructure in its continuous processes, enabling continuous and secure communication between devices, systems, and people, thereby optimizing operational efficiency and real-time responsiveness while addressing challenges such as cybersecurity, costs, and system integration.
Technical Assistance	Intensive training for operators on new technologies is crucial and can be a challenge in mining operations. The high initial cost of implementing these technologies can be a significant barrier. Integrating these solutions into continuous processes, such as ore transportation and processing systems, can be complex. Additionally, the ongoing need for maintenance and updates of technical assistance technologies, coupled with rapid technological advancements, may impact the effectiveness of the implemented solutions.	**Proposition 2:** The continuous mining industry can adopt technologies such as augmented reality and AI for real-time technical support, increasing accuracy and reducing failures, but requires investments in training and maintenance.
Decentralized Decisions	Aligning decentralized decisions with the strategic objectives of mining is a significant challenge. Maintaining data quality and consistency across various sections of continuous operations is essential to avoid ill-informed decisions. Decentralization can lead to a lack of coordination between different parts of the operation, such as crushing and screening. Additionally, data governance and the creation of decision models that ensure alignment with the mine's strategic goals are crucial for success.	**Proposition 3:** In the continuous mining industry, empowering autonomous systems and operators to make real-time, data-driven decisions aligns operations with company strategies, improving responsiveness to process changes. This decentralization reduces the need for direct supervision, while addressing challenges like data quality and coordination across operations.
Information Transparency	Ensuring the privacy and protection of sensitive data, such as information related to equipment performance and safety, is crucial. Managing information overload is necessary to prevent difficulties in identifying relevant data for continuous operations. Promoting a culture that values transparency and utilizes information productively is essential. Additionally, adopting appropriate tools and technologies to manage and interpret large volumes of data without overwhelming operators is a significant challenge.	**Proposition 4:** The continuous mining industry can ensure information transparency across its value chain by integrating technologies like blockchain and analytics platforms, enabling real-time access to critical data. This enhances coordination and decision-making while requiring strategies to manage data overload, protect sensitive information, and promote ethical data use.
Sustainability	Balancing the implementation of sustainable practices with the economic viability of mining operations is challenging, particularly in high-cost processes. Navigating specific and frequently changing environmental regulations, such as emission limits and waste management, is complex. The continuous innovation required to promote sustainability demands significant research and development efforts. Evaluating the long-term economic impact of sustainable technologies and fostering partnerships to advance sustainability initiatives are critical aspects for ensuring the success of these practices in mining.	**Proposition 5:** The mining industry is able to incorporate sustainability practices throughout all stages of its continuous processes, from design to operation, using technology to monitor and reduce environmental impact, thereby promoting a more eco-friendly and responsible operation.

virtual metrology, flexible structure production control, and holonic production units.

A comparative analysis revealed that some of the typical resources and enabling techniques present in both contexts have not yet been fully explored and applied in context 2, Industry 4.0, in Continuous Production Processes in the Mining Industry. Technologies such as the Crushing and Screening Digital System (CSDS), which were utilized in Context 1, offer valuable learning opportunities that can be adapted for Context 2.

B. PROPOSITIONS

The literature review provides valuable insights into the challenges and opportunities associated with Industry 4.0 in continuous processes within the mining industry. Based on this knowledge, empirical studies can develop propositions to test these factors. Bibliographic analysis also helps identify research gaps and extract relevant constructs that represent concepts to be empirically verified. From these constructs, propositions can be formulated to measure concepts. The theoretical framework not only defines the scope of the investigation and provides theoretical support but also establishes the state of the art of the studied topic, reflecting the researcher's knowledge and familiarity with the subject. In addition, it is important to highlight significant points and propose reflections for future studies, contributing to the continuous evolution of methodological approaches in production engineering [126].

Based on the main topics of interest related to Contexts 1 and 2, which address Industry 4.0 in continuous processes and the mining industry, five propositions have been developed. These propositions address issues such as the limitations of Industry 4.0, studies/applications, process characteristics, amount of data collected, and infrastructure and integration. **Table 15** presents a comprehensive overview of these factors.

These propositions open up research opportunities that can answer the following questions:

- Interconnection: How has the mining industry implemented the interconnection proposed by Industry 4.0 in its continuous production processes?

- Technical Assistance: How has the mining industry adopted the technical assistance practices proposed by Industry 4.0 in its continuous production processes?

Decentralized Decisions: How has the mining industry facilitated decentralized decision-making in its continuous production processes?

- Information Transparency: How has the mining industry created transparency in the information of its continuous production processes using the principles of Industry 4.0?

- Sustainability: What technologies, methods, and practices from Industry 4.0 has the mining industry utilized in its continuous processes to promote sustainability?

In addition to the research opportunities listed in Tab. 15 propositions this review identifies further avenues for exploration regarding the adaptation of building elements from Context 1 to Context 2. Specifically, it investigates whether strategies and technologies developed for continuous production processes in other industrial sectors can be effectively adapted for the continuous mining industry. This adaptation could provide valuable insights into how these resources can be tailored to address the unique challenges and requirements of the mining industry, thus broadening the applicability of Industry 4.0 principles and enhancing operational efficiency within this sector.

VI. CONCLUSION

This study explored the application of Industry 4.0 design principles in continuous processes, with a particular focus on the mining industry, through a systematic literature review. The investigation covered two contexts: (i) continuous processes in general, and (ii) continuous processes specifically within the mining industry. The analysis revealed that the principles of interconnection, technical assistance, decentralized decisions, information transparency, and sustainability play essential roles in adapting these processes to the Industry 4.0 paradigm.

One of the main practical contributions of this study is the synthesis of opportunities offered by Industry 4.0 for continuous processes within the mining industry. Technologies and practices that are widely used in other sectors, such as Automatic Virtual Metrology (AVM), holonic production units (HPU), Flexible Structure Production Control (FSPC), and advanced manufacturing clouds of things (AMCoT), have not yet been fully explored in mining. This gap represents a significant opportunity for the mining industry to adopt innovations to improve efficiency, control, and operational flexibility.

Additionally, the study identified the use of mining-specific technologies, such as the Crushing and Screening Digital System (CSDS). This demonstrates how specialized resources can be applied to overcome unique challenges such as material variability and extreme operating conditions. The proposed theoretical framework suggests that the mining industry can leverage the lessons learned and innovative solutions from other sectors to enhance its operations and address specific challenges more effectively.

The development of the theoretical framework was guided by the responses to each research question, which are summarized below.

R.Q.1: Demonstrated the connection between Industry 4.0 and continuous processes in the mining industry. Despite being a recent field of study, there has been a notable increase in publications since 2017 (Context 1) and 2019 (Context 2). This allowed for the identification of primary sources and globally cited documents, which were crucial for structuring the final framework.

R.Q.2: Examine the application of Industry 4.0, design principles (interconnection, technical assistance, information transparency, decentralized decisions, and sustainability) in continuous production processes, and the mining industry. Both contexts focused on technical assistance, shifting the human role to strategic decision making. Key resources and techniques were identified to guide future studies and identify opportunities.

R.Q.3: Identified that both contexts primarily address process optimization and control, reflecting a strong emphasis on technical assistance. This focus aligns with the growing need to enhance efficiency, reduce costs, and improve market competitiveness, indicating that process optimization is a priority in these contexts.

R.Q.4: Highlighted the main challenges in applying Industry 4.0 to continuous processes, such as the lack of specific studies, complexity, and financial risks of continuous processes, and unique challenges in mining, such as waste management and conveyor systems. Issues with infrastructure and control system integration as well as managing vast amounts of data were also identified.

R.Q.5: Identified knowledge gaps in applying Industry 4.0 principles to continuous processes in the mining industry. This study proposes a comprehensive theoretical framework that maps opportunities and provides practical guidelines, stressing the need for customized approaches.

By integrating insights from both general continuous production and specific mining challenges, the framework aims to advance Industry 4.0 technologies in mining, enhance efficiency, reduce costs, and increase competitiveness. This framework and propositions set the foundation for future empirical research by fostering innovation and digital transformation in the sector.

By synthesizing these opportunities, the framework provides a structured pathway for implementing Industry 4.0 technologies in the mining sector, promoting a practical approach to digital transformation. This suggests that adopting successful practices from other contexts can not only improve mining efficiency and competitiveness, but also prepare the sector for future challenges, ensuring its relevance and sustainability in the global landscape.

Furthermore, the study facilitated relevant academic discussions on future research directions and identified knowledge gaps that need to be addressed. These gaps offer opportunities for empirical investigations to validate the proposed framework and integrate new emerging technologies into the adoption of Industry 4.0, thereby contributing to advancing knowledge at the intersection of Industry 4.0 and continuous mining processes.

By addressing these two objectives, synthesizing practical opportunities, and facilitating future research, this study not only fills a critical gap in the existing literature but also provides a theoretical guide to promote innovation and digital transformation in the mining industry. This study suggests that mining industries can benefit from the experiences and solutions identified in other continuous process sectors, thereby providing a robust practical foundation for future industrial applications.

Study Limitations: This study presents a theoretical framework that recognizes that different mining industries have unique characteristics and that the implementation of Industry 4.0, which is complex and requires customized approaches. The conclusions were based on the available literature, which may have contained publication biases and limitations in the interpretation of the authors.

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