Iberoamerican Journal of Industrial Engineering

A PRELIMINARY AND EXPLORATORY SOLUTION FOR INTEGRATING CHARCOAL BLAST FURNACE IRONMAKING PROCESSES: ENHANCING INTEROPERABILITY IN A BRAZILIAN COMPANY

SOLUÇÃO PRELIMINAR E EXPLORATÓRIA PARA A INTEGRAÇÃO DE PROCESSOS DE FABRICAÇÃO DE FERRO EM ALTO-FORNO A CARVÃO ARTIFICIAL: AUMENTANDO A INTEROPERABILIDADE EM UMA EMPRESA BRASILEIRA

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ABSTRACT: The objective of this study is to propose a preliminary and exploratory solution for integrating charcoal blast furnace (BF) ironmaking processes, with a focus on enhancing interoperability within a Brazilian company. Many BF operations face challenges related to process and equipment interoperability, leading to a lack of integration between shop-floor systems and enterprise-level systems within the automation pyramid. To address these challenges, a systematic literature review was conducted, along with a case study in a charcoal BF ironmaking company. As a key outcome, a preliminary, exploratory solution is proposed to enable the seamless integration of independently controlled systems, auxiliary facilities, and business process management with real-time production processes. This integration is essential for driving digital transformation and improving operational efficiency within the company. The primary contribution is the development of a platform-based integrational solution that enhances interoperability through a hybrid approach. This study contributes to the literature by providing new perspectives and methods, which, in turn, serve as a foundation for improving connectivity, data exchange, and overall efficiency in the charcoal BF ironmaking industry.

KEYWORDS: Blast furnace; Ironmaking; Interoperability; Industry 4.0; Industrial IoT.

RESUMO: O objetivo deste estudo é propor uma solução preliminar e exploratória para a integração de processos de produção de ferro-gusa em alto-forno a carvão vegetal, com foco na melhoria da interoperabilidade em uma empresa brasileira. Muitas operações em alto-forno enfrentam desafios relacionados à interoperabilidade de processos e equipamentos, resultando em falta de integração entre os sistemas de chão de fábrica e os sistemas de nível empresarial dentro da pirâmide de automação. Para abordar esses desafios, foi realizada uma revisão sistemática da literatura, juntamente com um estudo de caso em uma empresa produtora de ferro-gusa em alto-forno a carvão vegetal. Como principal resultado, propõe-se uma solução preliminar e exploratória para permitir a integração perfeita de sistemas controlados independentemente, instalações auxiliares e gestão de processos de negócios com os processos de produção em tempo real. Essa integração é essencial para impulsionar a transformação digital e melhorar a eficiência operacional da empresa. A principal contribuição é o desenvolvimento de uma solução de integração baseada em plataforma que aprimora a interoperabilidade por meio de uma abordagem híbrida. Este estudo contribui para a literatura ao fornecer novas perspectivas e métodos que, por sua vez, servem como base para aprimorar a conectividade, a troca de dados e a eficiência geral na indústria produtora de ferro-gusa em alto-forno a carvão vegetal.

PALAVRAS-CHAVE: Alto-forno; Siderurgica; Interoperabilidade; Indústria 4.0; IoT industrial.

1. INTRODUCTION

The industry 4.0 concept was introduced at the Hannover Fair in 2011 by the German government. Since then, the Brazilian steel industry has changed substantially. The industry has expanded and consolidated, while also adopting Industry 4.0's technological clusters to enhance production processes. The deployment of secure, robust, and resilient data networks is now widespread (Paula, 2018). Brazil has abundant iron ore and charcoal resources, so blast furnace (BF) ironmaking remains dominant (Clark, 2024). The use of charcoal as a reducing agent in BFs (charcoal BF) is increasing. For example, more charcoal BFs with working volumes of 300–600 m³ have been commissioned in Brazil (Almeida *et al.*, 2018 ; Engel *et al.*, 2015).

With the rapid advancement of automation and intelligent technology in the steel industry, the intelligent upgrading of BF ironmaking is becoming prominent. Upgrading requires production management to ensure consistency over time and to balance material, energy, and information flows across all production processes (Javaid *et al.*, 2023). As a result, a fully integrated manufacturing and business system is essential to support real-time decision-making.

We have found that vertical integration remains a common issue in the steel industry. The research question "How can a unified framework be developed and applied in the charcoal blast furnace (BF) industry to improve interoperability in the hot metal production?" motivates our research. In the context, some researchers are exploring the topic of digital transformation and intelligent integration of blast furnace manufacturing production (Li *et al.*, 2021 ; Zhang *et al.*, 2021 ; Wang *et al.*, 2020). These researchers primarily focus on optimizing coke and large blast furnace production rather than on charcoal blast furnace ironmaking systems. They often overlook the specific characteristics and requirements of charcoal blast furnace operations because coke and large-sized blast furnace ironmaking currently account for a larger share of hot metal throughput worldwide. Thus, this research seeks to fill this gap in the literature by exploring new methods to facilitate the digital transformation and intelligent integration of the charcoal BF ironmaking industry.

The academic gap lies in the fact that traditional BF ironmaking data management is based on different business scenarios at various levels, making it difficult to achieve data flow and integrated processing across the upper and lower levels of the ISA-95 pyramid. The high complexity and variety of heterogeneous devices and technologies used across fields and control layers pose challenges for integrating BF ironmaking processes (Zhang *et al.*, 2021). To understand the actual situation, a systematic literature review (SLR) using PRISMA (Page *et al.*, 2021) was conducted. A case study was conducted at a charcoal-based BF ironmaking company in Brazil. From these efforts, it is concluded that the long-life cycles of BF automation and communication systems often lead to the continued use of legacy devices and protocols that were not designed to support modern interoperability standards (Ismail *et al.*, 2016). The lack of interoperability among BF ironmaking processes primarily causes a disconnect between the shop-floor system and the business system in the automation pyramid, thereby hindering integration (Seiger *et al.*, 2022 ; Govender *et al.*, 2019 ; Ismail *et al.*, 2019). Additionally, more than 300 IoT platforms are being developed annually in the current market (Aazam *et al.*, 2018). Therefore, transforming the BF ironmaking industry into an intelligent system requires integrating all systems and platforms into a unified architecture. This study aims to propose a preliminary, exploratory solution for integrating charcoal BF ironmaking processes, focusing on improving interoperability within a Brazilian company.

To address the emerging trend and increasing demand for intelligent transformation in the BF ironmaking industry, a platform-based, integrated solution for integrating charcoal BF ironmaking processes is proposed. It retains the core features of the industrial IoT platform and the basic structure of the ISA-95 pyramid with some functional modifications, combinations, and extensions. However, it designs the overall data architecture based on the actual production scenario of charcoal BF ironmaking processes.

The main contribution of the study is the development of a hybrid solution that improves interoperability. This research adds to the literature by offering new perspectives and methods, which provide a foundation for enhancing connectivity, data exchange, and overall efficiency in the charcoal BF ironmaking industry.

This paper is divided into six sections. The first section is the introduction. The second section covers the fundamental concepts of the automation pyramid, infrastructure technologies, and integration to enhance interoperability through a literature review. The third section introduces the case study. The fourth section examines the practical application of Industry 4.0 concepts within the case study company. The fifth section discusses related key concepts and technologies. The sixth section summarizes the project, its limitations, and future work.

2. LITERATURE REVIEW

The literature review summarizes the characteristics of BF ironmaking data, the problem with typical BF automation systems, and the intelligent automation system.

2.1 CHARACTERISTICS OF BF IRONMAKING DATA

In the application of the automation pyramid to BF ironmaking processes, the traditional platform architecture follows the ANSI/ISA-95 hierarchical automation pyramid, which defines 5 levels in a BF ironmaking company (Li *et al.*, 2022). These levels represent a structured system in which Level 0 underpins real physical ironmaking processes, Levels 1 and 2 focus on manufacturing automation, Level 3 employs monitoring to manage operations through key performance indicators, and Level 4 leverages ERP systems for comprehensive business operations across the supply chain.

SCADA is typically required for a process industry at Level 2, and MES is installed at Level 3. They are connected through standard interfaces and protocols. While most steel plants, especially smaller ones, have not yet installed MES. Moreover, with the advent of low-cost, smart sensors and subsequently Cyber-Physical Systems (CPS), sensors connected to machines are now accessible, as they can be addressed over the network via TCP/UDP on IP. Thus, MES can directly coordinate with the machines in the manufacturing plant without any time-compatibility issues. This development has raised the possibility of omitting Level 2 (Automation & Control) and delegating its responsibilities to Level 3 manufacturing execution. In many cases, SCADA systems and the connectivity solutions from Level 3 through SCADA to the shop floor have been vendor-specific. They do not follow industry standards, making it challenging to replace machines on the shop floor. The trend of moving towards standardized communication protocols at all levels of the automation pyramid also fosters the development of Level 2 circumvention. Figure 1 illustrates the practical positioning of the MES and SCADA within the automation pyramid (Katti, 2020).

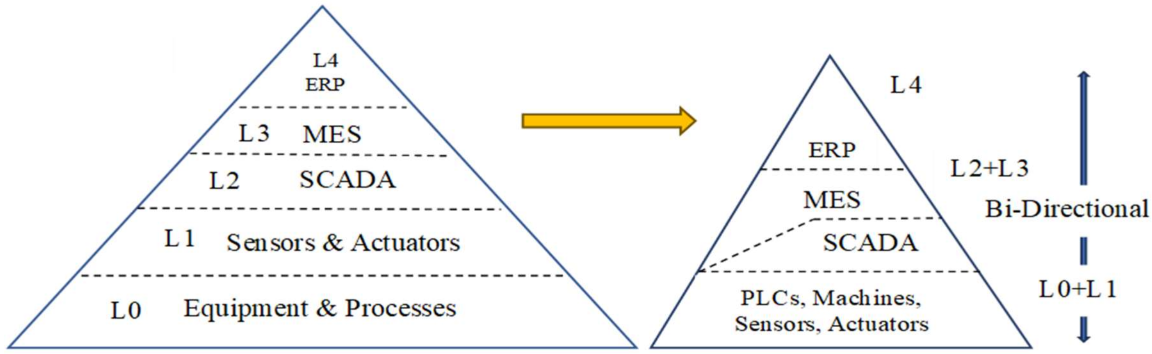

Figure 1 : Evolution of classical automation pyramid.

Source : Katti, (2020).

On the platform architecture, the BF production data are divided into real-time, quality inspection results, production operations, and audio/video data, which are stored in different databases based on their characteristics. The real-time data consists of output signals from programmable logic controllers and other sources, with large volumes stored at intervals of seconds, synchronized with on-site production data refresh times. Real-time information is organized in a single data table format with timestamps as keys (Li *et al.,* 2022; Zhang *et al.,* 2014). Quality data is collected from material inspections and testing throughout the entire process. Because testing involves a wide range of materials and methods, and some results require manual collection, noise in the data is common (Deng *et al.,* 2020; Sarmiento *et al.,* 2020). Production data is recorded both regularly and irregularly; regular data is recorded daily, while abnormal data is recorded as incidents occur. Most data are stored in text format, which limits usability and lacks standardization (Zhou *et al.,* 2022; Zou *et al.,* 2015). Audio and video data from the production environment are unstructured, making online querying and automatic identification difficult (Li *et al.,* 2021; Deng *et al.,* 2020).

The data management process is split into online and offline applications. Online applications handle tasks like data collection, real-time monitoring, early warning systems, and detailed analysis. These tools give operators insights into process parameters, quality metrics, potential alerts, and ways to improve operations. Offline applications focus on analyzing the entire manufacturing process, combining quality data for a complete assessment of all steps. This system highlights traceability, technical specifications, and quality analysis to address issues at critical points.

2.2 PROBLEMS OF A TYPICAL BF AUTOMATION SYSTEM

The literature review on existing BF ironmaking companies reveals clear data challenges across six areas: i) ineffective, unsynchronized, and inefficient data transmission (Li, *et al.,* 2022); ii) data sharing occurs in isolated silos (Zhang *et al.,* 2021); iii) limited data storage capacity affects data security and control, and semi-structured and unstructured data cannot be stored efficiently (Li *et al.,* 2022); iv) data processing is highly inefficient, leading to data quality issues due to inconsistency (Zhang *et al.,* 2021); v) data analysis is basic, constrained by storage limits, inefficient processing, and unclear data boundaries (Li *et al.,* 2022); and vi) data application is limited and lacks intelligence, with a shortage of expert databases (Wang *et al.,* 2020).

Generally, traditional automation systems cannot effectively address the heterogeneity of equipment and technologies in the BF ironmaking industry, nor can they efficiently enhance interoperability throughout the entire process to achieve data integration and eliminate data silos.

2.3 INTELLIGENT AUTOMATION SYSTEM

2.3.1 REQUIREMENTS FOR THE INTELLIGENT TRANSFORMATION OF BF IRONMAKING

The advanced transformation of BF ironmaking automation control and information system based on the industrial IoT framework aims to enhance the collection, transmission, processing, storage, analysis, and visualization of BF production and operational data using new information technology (IT) tailored to the actual production environment. It builds a data analysis platform and intelligent applications capable of addressing production challenges from Level 0 to Level 4 with emerging data technologies, supporting the digital and intelligent transformation of BF ironmaking. The requirements for this transformation are summarized in Table 1.

Table 1- Requirements for the Intelligent Transformation of BF ironmaking

Inform. Manag.	Requirements validated in the literature	Researched by:
Data collection	To interface with multi-source heterogeneities in different ways, such as fieldbus, wireless sensor networks, advanced sensors, and actuator technologies.	Li *et al.* (2022) Seiger *et al.* (2022) Zhou *et al.* (2022)
Data transmission	To achieve full coverage of the interface types for different transmission methods (protocols, message queues, log files, Web services, equipment signals, etc.), predominantly vertical, bidirectional communication within the automation Pyramid.	Seiger *et al.* (2022) Zhou *et al.* (2022) Ismail *et al.* (2019)
Data storage	To provide a variety of storage methods (file storage, relational storage, non-relational storage, etc.); to provide automatic backup of massive data to ensure data integrity and security; and to provide a convenient expansion interface to meet the needs of a business increase in the later stage.	Li *et al.* (2022) Zhou *et al.* (2022) Wang *et al.* (2020)
Data processing	To provide multiple ways and models to process data in cooperation, primarily through an expert database.	Seiger *et al.* (2022) Wang *et al.* (2020)
Data analysis	To provide data-assisted analysis functions, leveraging batch processing, stream processing, and real-time processing.	Seiger *et al.* (2022) Zhou *et al.* (2022)
Data application	To provide intelligent applications through data mining (such as online image recognition and analysis, equipment anomaly early warning, whole process data tracking, prediction of crucial production parameters, optimization decision of production status, etc.)	Li *et al.* (2022) Wang *et al.* (2020)
Data stability, fluidity, security	To provide the availability, maintainability, scalability, stability, and security of the industrial IoT framework to ensure ironmaking production and development.	Li *et al.* (2022) Zhou *et al.* (2022) Wang *et al.* (2020)

Source: The authors.

2.3.2 INTEROPERABILITY HANDLING APPROACHES IN IOT

IoT interoperability can be viewed from the perspectives of device interoperability, networking interoperability, syntactic interoperability, semantic interoperability, and platform interoperability (Noura *et al.,* 2019), as well as cross-layer interoperability and cross-system interoperability (Sari *et al.,* 2020). To enhance the current state of IoT interoperability, researchers have employed many approaches and technologies, summarized in Table 2.

Table 2- Interoperability handling approaches and technologies in IoT

Technologies		Contributions validated in the literature	Researched by:
Gateway		To bridge across different specifications, data, standards, middleware, etc. To convert the protocol between the sending device's protocol and the receiving device's protocol.	Zachariah *et al.* (2022) Asensio *et al.* (2014)
Virtual networks/overlay-based solutions		To integrate sensors, actuators, and other intelligent IP-smart devices seamlessly into the Internet framework for end-to-end communication. To create a virtual network atop physical networks, enabling communication across diverse device types, including sensors.	Ishaq *et al.* (2012) Hoebeke *et al.* (2011)
Networking technologies	IP-based approaches	To embed the entire TCP/IP stack on smart devices, the sensor and actuator components are directly connected to the IP network, enabling seamless end-to-end communication between the sensor and IP networks.	Jung *et al.* (2021) Thubert *et al.* (2012)
	Software-defined networking	To facilitate applications such as network heterogeneity, mobility management, quality-of-service optimization, and security measures, ensuring robust performance in diverse environments.	Bizanis *et al.* (2016) Nguyen *et al.* (2016)
	Network function virtualization (NFV)	NFV leverages shared infrastructure, dynamic resource allocation, and flexibility to reduce both capital and operational expenditures by optimizing hardware usage and ensuring adaptable cloud computing solutions.	Yi *et al.* (2017) Mijumbi *et al.* (2016)
	Cloud computing	Cloud computing enhances efficiency by minimizing network latency, which is crucial when transforming raw data from resource-constrained devices and sensors into actionable insights.	Ai *et al.* (2017) Gyrard *et al.* (2017)
Open API		To provide well-documented open APIs with cross-platform, cross-domain interoperability that allows developers to gain streamlined access to functionalities and services seamlessly.	http://www.openiot.eu http://thingspeak.com
Service oriented architecture		To allow different devices to communicate effectively with each other and across various systems.	Giao *et al.* (2022) Issarny *et al.* (2016)
Semantic web technology		A shared understanding among various IoT entities is essential. Semantic web technologies are crucial drivers for interoperability across diverse environments.	Belozerov *et al.* (2022) Lan *et al.* (2022)
Open standards		Open standards are one effective means of providing interoperability across and within domain boundaries.	Ning *et al.* (2020) Almeida *et al.* (2011)

Source: The authors.

The interoperability approaches are emphasized in the table above rather than their specifications.

3. METHODOLOGIES

To conduct this research, a systematic literature review (SLR) was performed. To verify and validate the SLR results, a case study was then conducted.

3.1 SLR

The objective of this study is to propose a preliminary, exploratory solution to integrate charcoal BF ironmaking processes, with a focus on enhancing interoperability within a Brazilian company. To ensure comprehensive outcomes in the specific domain, two databases—Web of Science and Scopus—are employed to retrieve publications from esteemed journals and institutions. Furthermore, keywords are carefully defined to facilitate an exhaustive study on the subject matter. The critical steps involved in selecting relevant publications are outlined below.

The articles were searched from 2011 to 2024 on Scopus and Web of Science using the initial keyword "blast furnace Ironmaking," resulting in 1,647 articles from Scopus and 1,262 from Web of Science. To identify relevant articles, the keyword "integrated blast furnace ironmaking" was used, yielding 115 articles from Scopus and 129 from Web of Science. Further refinement was done by searching for "intelligent blast furnace ironmaking," which found 54 articles from Scopus and 39 from Web of Science. In total, 93 articles were identified. Additionally, 7 articles were found closely related from the two databases in 2025. These were then screened by abstract for relevance, and 16 were excluded—either because they focused more on the reactor's reaction mechanism or were unrelated to the intelligent information system of the BF. This left 84 articles. After an initial review, 56 articles were retained for this review. The methodology, based on PRISMA 2021 (Page *et al.,* 2021), is summarized in Figure 2.

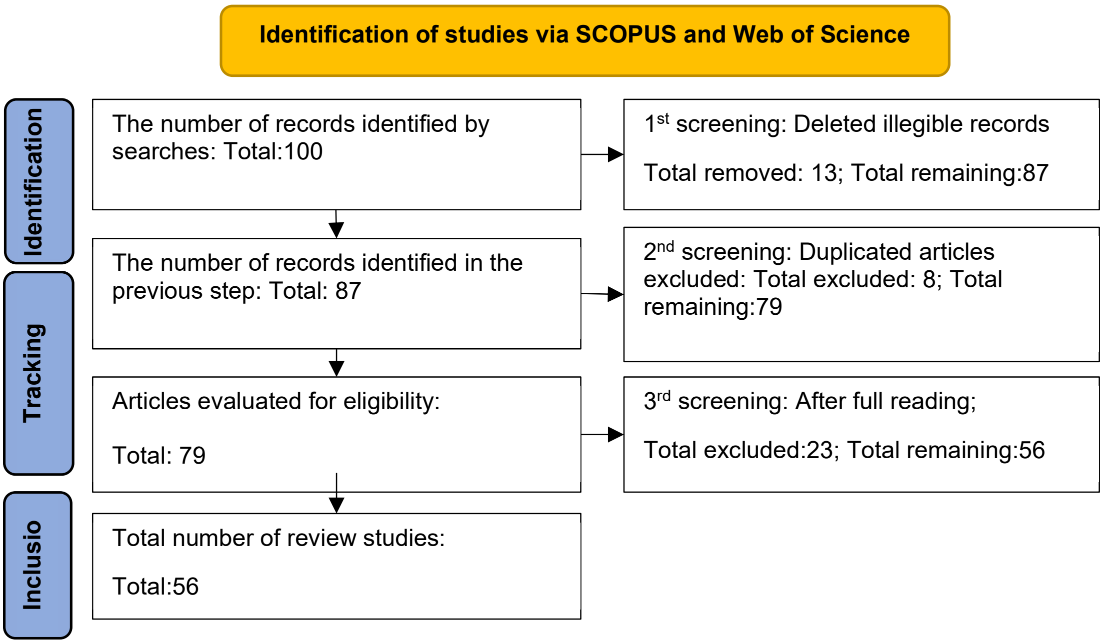

Figure 2: Flow diagram of Identifications.

Source: The authors.

All selected articles were analyzed in depth. They originate from reputable journals and universities, such as IEEE Transactions on Automation Science, the International Journal of Software Engineering & Application, Vienna University of Technology, and the University of Johannesburg, among others, making them highly reliable and credible. They are divided into three categories.

Category 1: Review and research the status and development of BF ironmaking processes through theoretical analysis and on-site inspection.

These articles examine the features and current issues of BF production data and reveal trends and integration in data collection, transmission, storage, processing, analysis, application, stability, fluidity, and security.

Category 2: Technologies for Interoperability in Industrial IoT

These articles present or summarize approaches and technologies for interoperability in IoT that facilitate the seamless integration of business process management with real-time production processes through theoretical analysis and experimental projects.

Category 3: Using modeling and trial tests on BF ironmaking industrial internet platforms.

These articles propose different industrial internet platforms for standardizing the integration by modelling and trial tests based on the ISA-95 automation pyramid. In the meantime, they ignore the advent of low-cost, smart sensors and Cyber-Physical Systems (CPS). The sensors connected to the machines are now reachable, as they can be addressed over the network via TCP/UDP on IP. They also omit that the charcoal BF ironmaking industry requires a low-cost, flat, and efficient internet platform.

In the charcoal BF ironmaking industry, there are very few related publications, which led to a case study at a charcoal BF ironmaking company in Brazil and a proposal for a flat, preliminary reference architecture in this regard.

3.2 CASE STUDY

Since the target of investigation is a typical BF ironmaking company whose organizations and manufacturing processes are out of control, the case study search is highly relevant (Yin, 2018). To conduct the case study, it is necessary to collect data, interview people, review documents, and make field observations in a company. Therefore, a questionnaire was designed in accordance with IEC 62264:201 and conventional practices to collect data, which later served as the guideline for the fieldwork.

In Brazil, the concentration of steelmaking is relatively high; some steel companies, such as those belonging to major steel groups in Brazil, are the best examples of the Brazilian steel industry, with large scale, and are typical and representative in Brazil. Therefore, the study was conducted at one of these companies, located in the city of Açailândia, Maranhão, Brazil, with a production capacity of 600,000 tons of steel per year. Its main products are wire rod, rebar, billet, and pig iron. The company has an ironmaking plant with two newly built charcoal BFs in operation. These two charcoal BFs started in 2018 and 2022, respectively, and are now operating at full capacity. Each has a working volume of 351 m^3, and the average daily production capacity is 1,000 tons of hot metal (HM), typical of large-scale charcoal BFs in Brazil. Additionally, to gather more information, another steel company in Jeceaba, Minas Gerais State, Brazil, was visited on October 16, 2024. This facility has one charcoal BF in operation, with a working volume of 350 m^3.

The fieldwork was conducted at the BF plant of the steel company twice. The first session was from June 10 to 21, and the second from August 27 to September 4, 2024. Throughout, the principle of double-checking was strictly adhered to, and interview excerpts, field notes, document excerpts, and photos of devices and equipment were collected to ensure the case study's validity. The company data collected was anonymized and authorized for use.

The fieldwork involves key-person interviews, document review, and observations of all iron-making processes. Afterwards, all collected data, photos, and videos were validated, enabling characterization of the existing BF automation system and network setup.

Since the physicochemical reaction mechanism of BF processes is the same worldwide, the BF ironmaking production layout and configuration are nearly identical, with iron ore as the primary raw material for producing hot metal. Therefore, the pattern matching technique (Yin, 2018) and qualitative comparative analysis (Pattyn *et al.,* 2017) were adopted to compare the case study results with advanced BF ironmaking patterns, aiming to identify weak points and develop a preliminary reference architecture for the ironmaking system and process integration of the charcoal BF ironmaking company, based on the architecture and construction guide for intelligent ironmaking systems (Wang *et al.,* 2020).

4. OPERATIONS IN INDUSTRY 4.0 CONCEPTS WITHIN THE COMPANY

The section included the BFs' indexes, a comparison between the case study data and the theoretical concepts introduced in Section 2, and a preliminary reference architecture for integrating charcoal BF ironmaking processes.

4.1 DESIGN AND OPERATION INDEXES

The basic data, production indexes, and raw material indexes of the two charcoal BFs from the case study company are listed in Table 3 and were analyzed and compared with those of advanced, similarly sized charcoal BFs.

Table 3- Design and operation indexes of the case study company's two BFs

Index	Description		No. 1 BF	No.2 BF
Basic data	Start-up		2018	2021
	Average capacity		1000t/day	
	Useful volume		351 m^3	
	Hearth diameter		5.2m	
	Useful height		17m	
	Tuyere No.		15 pcs	
	Charging system		Double cones	
Production index	Productivity			
	Monthly average		592.03 tpd	583.40 tpd
			1.69 $t/m^3 \cdot d$	1.66 $t/m^3 \cdot d$
	Monthly best		909 tpd	801 tpd
			2.59 $t/m^3 \cdot d$	2.28 $t/m^3 \cdot d$
	O_2 Enrichment		2~4%	
	Blast volume		42,000 Nm^3/H	
	Blast temperature		800^0C	
	Blast pressure		0.45ba	
	Permeability		5.10~7.0 Nm^3/mmCa	
	Energy consumption		114.24 kWh/t	
Raw Material indexes	**Lump ore**			
	Ore		1473 kg/tHM	1516 kg/tHM
	Size		6.3~25(±10% out of range)	
	Reductant (Charcoal)			
	Consumption	Lump	540kg/tHM	
		Fine	90 kg/tHM	
	Analysis:			
	Fixed carbon		77%	
	Volatiles content		18%	
	Sulfur content		0%	
	Ash content		1.5%	
	Bulk density		270 kg/m^3	
	Size		>25mm (±10% out of range)	
	Fluxes			
	Limestone		135 kg/t	137 kg/t
	Dolomite		22 kg/t	19 kg/t
	Laterite		250 kg/t	249 kg/t
Operation indexes	Si content of pig iron		0.2%	
	Pig iron temperature		1385^0C	
	Sulphur content of pig iron		0.02%	
	Slag ratio		300 Kg/tHM	
	CaO/SiO_2 of slag		0.7%	
	Al_2O_3 content of slag		19%	
	MgO content of slag		6.5%	
	Liquidus temperature		<1300^0C	
	Top gas temperature		~100^0C	

Source: The company.

From the table above, the production, raw materials, and operation indexes of the two charcoal BF were compared with the main indexes of similar-sized charcoal BFs as follows:

1) Production index: the average monthly production volumes are 592.03 tpdHM and 583.40 tpdHM, respectively, which are 59.203% and 58.34% of the design index. The average monthly best production volumes are 909 tpdHM and 801 tpdHM, respectively, which are

90.9% and 80.1% of the design index. The results indicate that there is much room to improve and optimize the production index. For example, the blast volume and temperature could be increased from 42,000 Nm^3/H and 800^0C to 45,000 Nm^3/H and 1100^0C respectively. The oxygen enrichment could be increased from 2~4% up to 7%. These actions will significantly increase the production index according to the practice and analysis of Almeida *et al.* (2019) and Engel *et al.* (2015).

2) Raw material index: fine charcoal is injected through the tuyeres, which decreases the lump charcoal charged through the top of the BF, which leads the fuel ratio go down. The current fine charcoal consumption is 90 kg/tHM, which could be increased to 150~180 kg/tHM according to the practice and analysis of Almeida et al. (2019) and Neiva et al. (2011). As a result, lump charcoal will decline significantly.
3) Operation indexes: the slag rate (300 Kg/tHM) is almost double the normal charcoal BF slag rate, as indicated by Scarpinella *et al.* (2011), which leads to more fuel consumption. While the ash content of the charcoal is only 1.5%, so, the main reason for the high volume of slag comes from the fluxes and iron ore. It is suggested to use a refined burden, such as a pellet, to reduce the slag ratio and increase the charging system capacity, thereby improving productivity.

4) During the case study, it was found that charcoal powder leakage and floating in the air were serious during charcoal transportation, sieving, conveying, milling, and charging. It is suggested that the power of the dedusting systems should be increased, and that the conveyors for charcoal powder should be entirely covered by hoods and sealed.

4.2 COMPARING THE CURRENT AUTOMATION SYSTEM OF THE COMPANY WITH THE REQUIREMENTS FOR THE INTELLIGENT TRANSFORMATION OF BF IRONMAKING

The company's ironmaking automation control system includes central process control systems and independent control systems, as shown in Figure 3.

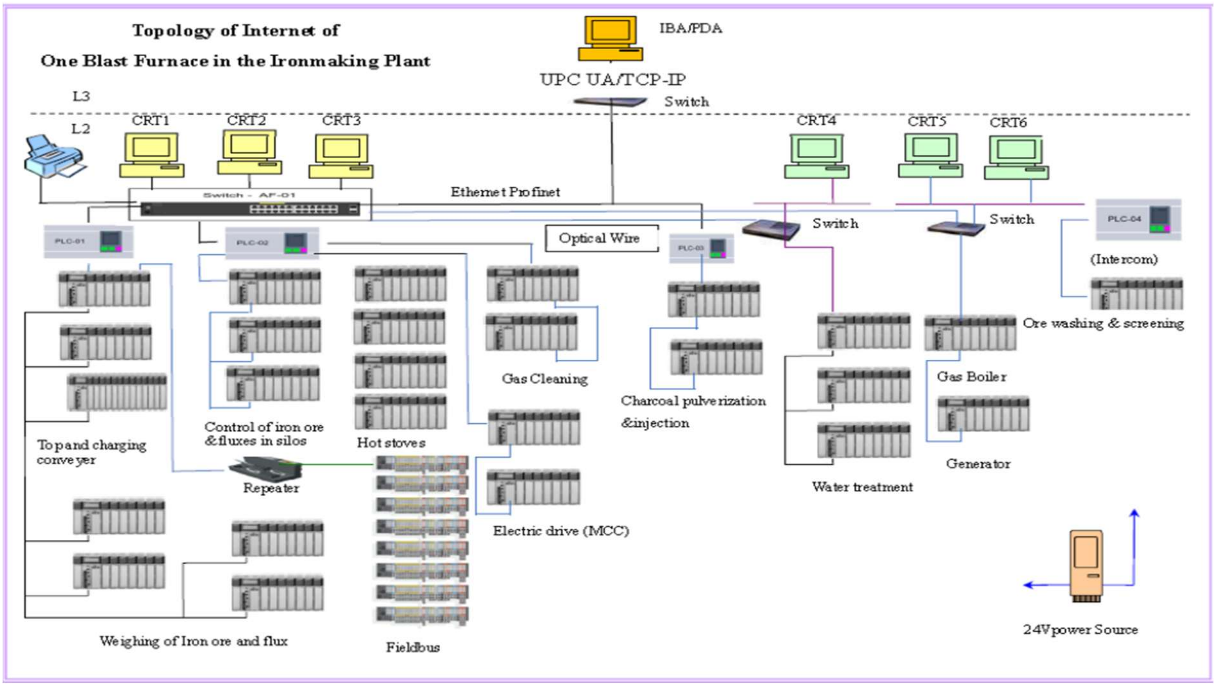

Figure 3: Diagram of the BF automation system and network configuration.

Source: The authors.

Figure 3 shows that the central process control systems have become a unified control and communication system based on PLC and an industrial IoT platform. In contrast, the independent control systems are mainly manually controlled and separated, based on end-to-end communication. In this situation, all the problems of data collection, transmission, sharing, storage, processing, analysis, and application in the present BF ironmaking industry, as indicated in Section 2, do exist and worsen in the case-study company, directly resulting in low labor productivity in the BF plant.

From Table 3, the average output of hot metal of the two BFs in the year 2023 is 17,761 t/month +17,502 t/month= 35,263 t/month×12=423,156 t/year. The management document of the plant shows that there are 219 staff and workers. So, the average labor productivity of the plant is 423,156/219=1,932 tHM/year/man of the year 2023, which is equivalent to the level of BF ironmaking in China about 20 years ago. Because, in 2000, 2001, and 2002, the BF techno-economic indicators for key ironmaking plants in China were 1791.00 tHM/year/man, 1968.00 tHM/year/man, and 2161.65 tHM/year/man, respectively (Wang, 2009). Moreover, the productivity of the two BFs is not only low but also unstable compared with charcoal BFs of similar size (Almeida *et al.* 2019; Engel *et al.* 2015).

The circumstances of the two BF operations result from many factors. From a data communication perspective alone, the root causes of the notable phenomenon are reflected in the following:

- Data collection and transmission

In the central monitoring and control system, data is mainly collected automatically, and transmissions are via fieldbus and Ethernet, or radio and telephone. In the independent control system, data collection is primarily manual, and transmission is via radio intercom, telephone, or meetings. Different types of data are collected and transmitted in different ways. It is not easy to achieve simultaneous and efficient data collection and transmission across all data types. Since the ironmaking processes and systems are scattered across different locations and over long distances, manual data collection requires a lot of manpower, and data transmission involves end-to-end communication with poor quality.

- Data sharing and storage

The BF ironmaking plant has two control rooms and three material testing rooms, as well as the control rooms of the water treatment and power generation stations, and various control panels next to machines, resulting in severe upstream and downstream data islands, especially for offline data. Data storage has upper limits for different storage systems. Massive production data cannot be stored effectively, and the data are either discarded or unreasonably archived. Traditional relational databases cannot efficiently store semi-structured and unstructured data. And all those posts that are manually operated and inspected are difficult to store data for long periods and share across the whole production stream.

- Data processing and analysis

In the BF ironmaking plant's central monitoring and control system, the technical team effectively performs data processing and analysis both online and offline. But they are still highly inefficient in handling large amounts of data from business requirements and charcoal supply situations. Even though it can perform real-time dynamic analysis of raw materials, charcoal preparation and injection, and operating parameters, and adjust ironmaking operations promptly, it still lacks intelligent functions such as equipment status warnings, production status predictions, and optimized operational decisions. In this case, many meetings must be held routinely to process and analyze data offline, which not only wastes time but also yields non-objective results.

- Data application

The data application remains insufficient and requires operator assistance. For example, when abnormal data appear in the material-distribution equipment on top of the BF, it still requires experienced operators to climb up to the top to check the problem. The data application still relies heavily on the knowledge and experience of some highly skilled operators and engineers to assess process and equipment conditions and take preventive measures to mitigate production and equipment problems.

There are no quarterly, monthly, or daily iron-making production plans in operation. The production operation plan is input manually to guide the entire BF production.

In this case, a unified, open, and flat preliminary reference architecture was designed and proposed for the company in reference to the new research results of Chu *et al.* (2025), Liu *et al.* (2025), and Liu R. *et al.,* (2025).

4.3 A PRELIMINARY REFERENCE ARCHITECTURE FOR INTEGRATING CHARCOAL BF IRONMAKING PROCESSES

To seamlessly integrate the independent control systems, auxiliary facilities, and business process management with real-time production processes, and to enable collaborative interaction across the cross-systems, cross-platforms, and cross-fields of the charcoal BF company, a unified, open, and flat preliminary reference architecture for the charcoal BF ironmaking information system is proposed. It consists of only four levels, rather than the traditional five-level automation architecture, as shown in Figure 4.

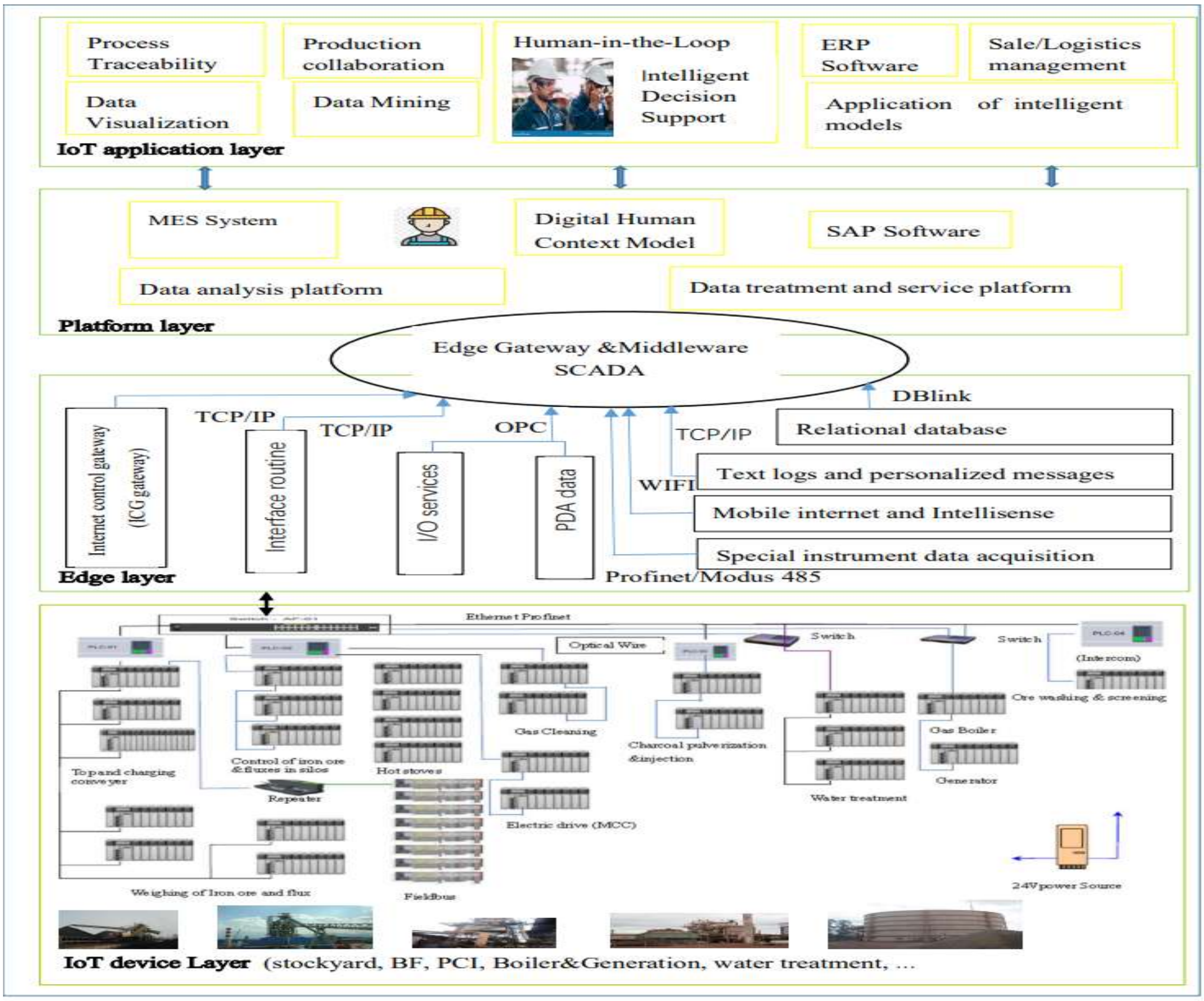

Figure 4: A preliminary reference architecture for integrating charcoal BF ironmaking processes.

Source: The authors.

As illustrated in Figure 4, the BF preliminary reference architecture comprises the IoT device layer, edge layer, platform layer, and IoT application layer.

IoT device layer: This layer applies IoT technology in ironmaking processes, requiring fast and precise collection of parameters to ensure efficiency, cost savings, and quality during manufacturing (Zhou, *et al.,* 2022). Equipment such as condition monitoring, temperature detection, defect inspection, and online inspections is used throughout the process. This layer includes the traditional Levels 0 and 1 of the automation pyramid (ISA-95). This approach offers several benefits for charcoal BF operations, enabling sensor data to be interpreted and translated into increased efficiency, interoperability, and scalability; it acts as the direct link between physical hardware and the logical "brain" that controls it.

Edge layer: This layer acts as the foundation for IoT technologies. It offers basic networking support and enables quick data transfer over both wireless and wired networks (Wang *et al.,* 2020). The large volumes of data produced in various formats must be transmitted in real time across multiple networks to ensure efficient operations. Data transmission primarily occurs through wired networks, such as optical fiber, fieldbus, and industrial Ethernet, as well as wireless networks. The Edge and Device layers aim to eliminate isolated and heterogeneous hardware systems, unify the infrastructure architecture by enhancing the basic automation capabilities of field devices, and integrate data communication with switches, gateways, and/or middleware. A communication model is embedded between the Edge layer and the Platform layer to ensure compatibility with all access networks and underlying protocols while maintaining the sensitivity, timeliness, and accuracy of data transmission in both directions. Typically, a blast furnace plant should provide data transmission guarantees with a latency of 20–40ms. Additionally, a hybrid interoperability approach is adopted at the IoT device layer and the Edge layer. The mechanism for utilizing gateways, switches, middleware, standards, APIs, or their combinations depends on the specific situation, budget, legacy devices, and protocols of the charcoal BF ironmaking company. For example, in the case study company, both gateways and switches, along with protocols, are used to integrate the fieldbus and Ethernet.

Platform layer: The layer creates and manages the service. It is a data collection, transmission, analysis, and sharing center of cross-systems, cross-platforms, and cross-fields, which collects structured, semi-structured, and unstructured data from the Edge layer. Then it proceeds to data integration, modeling, analysis, management, and services with a knowledge database (Li *et al.,* 2022). The platform layer shall eliminate shelf-made databases, and build a unified data storage through the combination of the data storage of BF, PCI, water treatment, cast house system, slag granulation system, iron ore receiving, screening and washing system, charcoal receiving, testing and processing system, electricity generation with top gas, and pig casting machine.

IoT application layer: This layer provides interaction mechanisms between users and other software/hardware systems, which involves intelligent modeling, innovative application development, intelligent control software, and a platform environment for system configuration (Zhou *et al.,* 2022). It handles data-driven visualization, advanced analytical capabilities, intuitive decision-making tools, and intelligent modeling applications. It is dedicated to building a closed data loop of state awareness, real-time analysis, scientific decision-making, and accurate execution through data visualization, historical data mining, and the application of intelligent models, thereby enabling the dynamic and efficient allocation of manufacturing resources across the ironmaking plant.

The open and flat preliminary architecture refines the traditional automation pyramid in the application of charcoal BF ironmaking operation and control systems with a hybrid of solutions by selection and/or combination of communication linking devices and technologies such as gateway, switch, middleware, IP-based approaches, etc., as per individual charcoal BF ironmaking company situations, which not only highlights the critical and decisive functions of human in the loop, but also facilitates AI technologies and humanoid robots to replace men, or at least reduce men's work in the casting house in the extremely hot and unsafe environment, measuring hot metal temperature and breaking out the taphole. AI technology inspires the expert system that can render scientific decisions promptly throughout the entire ironmaking process.

After successful construction, the IT structure will not only significantly increase the technological strengths and labor productivity of the charcoal BF ironmaking plant, but also boost the modern transformation of the behavior, culture, norms, manpower, management, etc. of the whole company, and, in turn, enhance its competitive power in the world.

5. DISCUSSIONS

This section covers the following issues: i) the initial reference architecture for integrating BF ironmaking processes; ii) IoT devices and basic automation; iii) heterogeneity and interoperability; iv) the elimination of isolated heterogeneous hardware systems and the unification of infrastructure architecture.

i) The preliminary reference architecture for integrating BF ironmaking processes

Many charcoal-based BF operations in Brazil face challenges related to process and equipment interoperability, primarily due to the lack of integration between shop floor systems and enterprise-level systems within the automation pyramid. To address these challenges, after an SLR and a case study of a charcoal BF ironmaking company, a preliminary reference architecture is proposed to enable the seamless integration of all independent control systems, auxiliary facilities, and business process management with real-time production processes. This integration is essential for driving digital transformation and improving operational efficiency within the company. The primary contribution is the development of a unified, open, and flat platform-based integration reference architecture that leverages a hybrid approach to enhance interoperability in charcoal BF ironmaking processes, serving as a foundational step toward improving connectivity, data exchange, and overall process efficiency in the BF ironmaking industry.

The proposed preliminary reference architecture adopts new IT technologies and reduces the traditional five-level automation architecture to four levels to facilitate the integration of charcoal BF ironmaking processes. The solution emphasizes human roles, such as chief process engineer and chief operator, and integrates flexibility across all system levels. This architecture differs from others and can be generalized to other industries with similar processes. The system is simple, low-cost, and easy to implement, and is practical for charcoal BF operations. Extending this approach to other industries in Brazil without new research presents unique opportunities.

ii) IoT devices and basic automation are the basis for enhancing the interoperability in the reference architecture

In the proposed preliminary reference architecture, IoT devices and basic automation are the basis for enhancing the interoperability of charcoal BF ironmaking processes and transforming the traditional BF ironmaking industry toward Industry 4.0. The case study found that the company still relies on manual handling of field devices and methods, which not only requires substantial manpower but also reduces productivity, increases communication heterogeneity, and hinders data communication.

As Wang *et al.* (2022) point out, modern BF ironmaking production should increase its automation rate to over 60%. Only in this case could the charcoal BF ironmaking company operate efficiently and achieve good results.

iii) Heterogeneity and interoperability

The heterogeneity of IoT devices is the main cause of interoperability issues in BF ironmaking processes. The study recommends a set of solutions for interoperability, including communication links between devices and technologies (middleware, gateways, and switches), the IEC 62264 series of international standards, and other approaches, customized to the specific needs of each BF ironmaking plant to enhance interoperability.

iv) Elimination of isolated heterogeneous hardware systems and unification of infrastructure architecture

Charcoal BF ironmaking is a collaborative process involving multiple units and hardware systems. Some hardware systems, like the weighing instruments on the conveyor belts of the charcoal BF plant, have been built using different communication protocols over time. Many systems, such as fully independent control systems, are still operated manually and separately, each with its own communication infrastructure. Only when these isolated, diverse hardware systems are unified on a standard communication architecture can the full integration of the charcoal BF automation pyramid be achieved.

6. CONCLUSIONS

The objective of this study is to propose a solution to integrate charcoal BF ironmaking processes, with a focus on enhancing interoperability within the Brazilian industry. Through the SLR and the case study, the primary contribution is the development of a unified, open, and flat platform-based integration architecture, leveraging a hybrid approach to enhance interoperability in charcoal BF ironmaking processes, which enables the seamless integration of independently controlled systems, auxiliary facilities, and business process management with the real-time production processes. It serves as a foundational step toward improving connectivity, data exchange, and overall process efficiency in the company. The solution is not only suitable for the charcoal BF ironmaking industry but could be generalized to other similar process manufacturing operations, such as continuous lime and cement kiln calcination, sintering, and pelletizing, to integrate all their production processes and enterprise operations. The adaptation and corrections to the unified, open, and flat preliminary reference architecture should meet the de facto requirements of different plant or process types within a reasonable budget; for example, constructing a rotary lime kiln plant requires less investment with much fewer auxiliary facilities. The fundamental processes of a rotary lime kiln plant include limestone crushing, sieving, conveying, charging, preheating, denitrification, calcination, cooling, discharging, testing, packaging, and delivery. The integrated processes also include the treatment of fuel, water, waste, gases, and oil. The control and automation systems should integrate all central and separate systems into a single platform, as proposed in the preliminary architecture with the hybrid interoperability approach. But at the platform and application layers, it is unnecessary to employ all those applications, such as the MES system and some intelligent models in the lime plant, as in the charcoal BF ironmaking plant.

As limitations, the SLR was based on two databases, with the majority of selected articles not from Brazil. More specialized databases, such as ABM Brazil, CNKI China, and the Indian Iron and Steel Database, contain articles on BF ironmaking technology and management that have not yet been fully retrieved. The pattern-matching technique and qualitative comparative analysis were adopted to analyze the collected data without simulation and verification. There were not enough cases available to conduct the case study during the research period. The study's results are primarily dependent on the case-study company's demands and on the availability of IoT technologies and interoperability solutions. The practical implementation of the platform-based integration architecture still needs to be controlled within budget, and it should be adapted to the de facto scenario when employed in other charcoal blast furnace companies and similar process manufacturing operations.

In this case, in the future, it is desired i) to continually optimize the proposed model, verify and refine the data integration in the charcoal ironmaking company; ii) to estimate and economize the cost of implementation of the solutions; iii) to have the proposed model adopted and executed in more charcoal blast furnace companies and similar process manufacturing operations; iv) to develop applications of AI technology in charcoal blast furnace companies; v) to search for supplementary data on charcoal BF ironmaking technology and management from more specialized databases.

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ARTICLE HISTORY

RECEIVED: 19-07-2025

ACCEPTED: 15-12-2025