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ARTICLES

New insights into the diffusion of I4.0 in the Brazilian Steel Industry: speed of adoption, effects on innovation systems, and financial results

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ABSTRACT

This article seeks to enrich the literature on innovation and the transformation of productive structures by exploring Industry 4.0 technologies and their applications and implications for the Brazilian steel industry. Through a comparative analysis of surveys conducted with the same companies in 2018 and 2021, the study tracks the evolution of I4.0 technology diffusion within Brazilian steel firms. The findings reveal that while the rate of diffusion of technological clusters in this sector has been relatively slow and has had limited impacts on the steel innovation system, the financial outcomes have been notably positive. Consequently, these innovations serve as effective tools for enhancing the existing productive structure in terms of availability and financial returns rather than revolutionizing it.

Keywords: Industry 4.0; Sectoral system of innovation; Diffusion of innovation; Steel industry, Brazil

1. Introduction

Industry 4.0 (I4.0), often referred to as the fourth industrial revolution (4IR), has attracted significant attention from businesses, governments, and scholars alike. Recent advances in the digitalization of economies have prompted investigations into the extent of the degree of I4.0 diffusion (whether high or low), its effects (widespread or specific), and its characteristics (radical or incremental).

In a prior study examining the application of I4.0 technological clusters in the steel industry published in 2021, we examined three main themes. First, we looked at the varying rates of adoption among different clusters, illustrating that within I4.0, technologies experienced diverse rates of dissemination. Second, we found that when these technological clusters were combined, they were more indicative of incremental rather than radical innovation. Third, the technological clusters have not significantly changed market structures, benefiting existing players more than potential newcomers do.

Given the evolving nature of I4.0, we deemed revisiting this topic worthwhile. Fortunately, we employed the same sample of enterprises as in our previous study, enabling us to not only assess the degree of diffusion but also scrutinize the speed of adoption within the same companies over time. We consider this to be a critical aspect of our research.

In our initial study, we touched upon the implications of I4.0 technological clusters for the sectoral system of innovation (SSI). In this revised questionnaire, we aimed to deepen our analysis by focusing on the interactions among various actors, including inquiries about innovation hubs to gauge Brazilian steel companies' engagement in open innovation schemes. Additionally, we posited that I4.0 technological clusters could yield favorable financial returns due to relatively low investment requirements and quick results. However, this deduction was more qualitative in nature and was drawn from the literature. To enhance the accuracy of this inference, our new questionnaire seeks information on the time-to-return of investments associated with I4.0, both past and prospective.

The article is structured into six sections, starting with this introduction, followed by a section outlining the theoretical framework underpinning the study. The subsequent sections review the relevant academic literature on I4.0 in the steel industry, describe the methodology employed, discuss key research findings, and conclude with a summary of the main insights.

2. Theoretical foundations

In the discourse surrounding I4.0, the primary focus revolves around its diffusion (high or low), impacts (widespread or specific), and nature (radical or incremental). The effects of I4.0 innovations tend to be differentiated depending on the technology, within the range of those commonly considered under the umbrella I4.0 (ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT, 2017).

In terms of the nature of these changes, Schwab (2017) asserts that I4.0 should be viewed as revolutionary, signaling profound transformations not only in the economic realm but also in social and cultural domains. However, some economists argue that these technological advancements are more incremental than radical, as they do not necessarily disrupt the progress made during the previous era of the 3rd Industrial Revolution (I3.0 or 3IR) (NUVOLARI, 2019; BRIXNER et al., 2020).

In a recent study exploring the nature of I4.0, Lee and Lee (2021, p. 157) conducted an extensive analysis using patent data. They focused on five major technologies (or technological clusters, which is the terminology employed in this paper): a) the internet of things (IoT); b) artificial intelligence (AI); c) robotics; d) additive manufacturing/3D printing; and e) big data (BD) and cloud computing (CC). The primary conclusions drawn from their study can be summarized as follows:

> [...] the 4IR is not a new revolution but an evolution into the second stage of 3IR because those five 4IR technologies are neither a radical break from the past nor pervasive. The difference

> between the 4IR and the 3IR becoming insignificant in terms of relative values reflects the important fact that the average values of cycle time, originality, and science-based-ness have all been increasing across all sectors over time or since the 2000s.

Lee and Lee's (2021) analysis delves into the significant impacts on the economic landscape stemming from the proliferation of the technological clusters constituting I4.0. Their noteworthy insights, replicated below, helped shed light on these impacts:

> If we take the so-called 4IR as not a new IR but a new or second generation of 3IR, these increasing trends of these key regime variables can be taken as the important aspect of the generation change or technological evolution. In other words, technologies in the 21st century are becoming more heavily reliant on science, combining knowledge from more diverse fields (higher originality) and becoming longer cycled but having an impact on less diverse fields (lower generality). These changes are happening not just in a few technologies commonly associated with the so-called 4IR but across the board of technologies (LEE; LEE, 2021, p. 157).

Similarly, Martinelli, Mina and Moggi (2021) study reached comparable conclusions concerning whether I4.0 technologies could be classified as "general-purpose technologies," that is, if they present the characteristics of pervasiveness (wide possibilities of adoption across sectors), dynamism (high potential for increasing efficiency), and the ability to generate complementarities (its adoption stimulates subsequent technical progress). By utilizing a patent database, they reveal notable heterogeneity, suggesting that only BD and AI currently embody the characteristics of "general-purpose technologies", whereas others are better categorized as "enabling technologies."

Filippucci et al. (2024) also explore the "general-purpose technologies" characteristic of AI, emphasizing its potential compared with previous technologies. Their recent study underscores AI's ability to achieve greater autonomy, self-improve, and accelerate the innovation process. Despite recognizing the uncertainties associated with AI development, the study identifies clear opportunities such as increased productivity, along with notable risks, including heightened inequalities and challenges to social inclusion. In terms of AI diffusion, the research reveals a slow overall pace with a U-shaped adoption pattern, with higher adoption in both younger, more entrepreneurial firms and older, more established companies.

The characterization of I4.0 technologies as more evolutionary than revolutionary, as argued by Lee and Lee (2021) and Martinelli, Mina and Moggi (2021), does not diminish the importance of ongoing changes and their potentially diverse impacts on countries, sectors, and companies. The evolution of I4.0 from I3.0 is described as "*iterative, nonlinear, nondeterministic, complex, blurred, and dynamic*" in a systematic literature review conducted by Peerally et al. (2022). This aligns with the Neo-Schumpeterian approach, which emphasizes the heterogeneity among countries (CASTALDI et al., 2009), sectors (PAVITT, 1984), and companies (DOSI et al., 2010).

Regarding effects on sectors, there is a common belief that I4.0 technologies hold the potential to instigate substantial transformations in various SSIs. The latter approach considers that the actors, types and structures of relationships and networks of firms vary significantly across sectors owing to distinct knowledge bases, learning processes, technological characteristics, demand factors, key connections, and dynamic complementarities (MALERBA, 2002). This concept accentuates, at a sectoral level, the issues of institutional complexity and diversity that characterize innovative activities, as pioneered by Nelson and Winter (1982) and, later, deepened in several studies by evolutionary economists, as recapitulated by Dosi and Nelson (2018).

The changes caused by I4.0 tend to be uneven and might transform SSIs in many dimensions. According to Li et al. (2021, p. 130), "[…] changes brought by 4IR open windows of opportunities for interesting interactions among various players both within and across sectoral systems. Firms' different strategic responses toward these changes will affect the innovation, evolution, and dynamics of various sectoral systems".

The increasing importance of universities and research centers in SSIs is acknowledged due to the scientific foundation of I4.0 technologies. While Lee and Lee (2021) find no significant departure from I3.0, they emphasize that the innovative essence of I4.0 lies in the amalgamation and reshaping of knowledge across various domains. This fusion has the potential to create new technological paradigms that align with Neo-Schumpeterian principles. It fosters novel interactions in innovation, particularly within buyer–supplier dynamics (PATRUCCO et al., 2022), and influences SSIs in diverse ways.

The extensive application of scientific knowledge in the automation and digitalization processes within factories has led to significant changes. These alterations include a) the utilization of new raw materials and increased adoption of electronic systems in the production process; b) the shift in the skill requirements of workers, such as the need for data analysts; and c) the trend toward enhanced integration of services into final products (PRIMI; TOSELLI, 2020). These transformations have the potential to impact relationships between producers and suppliers along the value chain. While the digitalization process necessitates a new set of services, it may also lead to heightened outsourcing, although challenges such as cybersecurity could hinder this trend.

With respect to businesses, the diffusion of I4.0 technological clusters can spur the emergence of new business models, shifts in the competitive landscape, and even alterations in market structures. In regard to competition, research based on patent data, such as that conducted by Lee and Lee (2021), reveals a significant predominance of I4.0-related innovations by a small number of global companies. This dominance is currently more pronounced than what was observed for technologies associated with I3.0.

Studies at the firm level aiming to capture the outcomes of implementing I4.0 technologies remain limited. One such study by Benassi et al. (2022), which focused on patents related to I4.0, revealed a significant and positive correlation between a company's inventory of 4IR patents and labor and overall factor productivity, particularly in 4IR-related wireless technology and areas such as AI, cognitive computing, and BD analytics. These findings hold particular significance for organizations with a substantial history of 4IR patents, underscoring the importance of firms' accumulated experience in achieving positive results (emphasizing the concept of cumulativeness, which is pertinent to the Neo-Schumpeterian approach). Nonetheless, the authors note that these gains have not yet translated into increased profitability.

Nevertheless, at the firm level, it is acknowledged that investments linked to I4.0 prompt changes in relationships between companies, fostering the reinforcement or establishment of new interactions. Patrucco et al. (2022) highlighted the importance of bolstering collaborative relationships between buyers and suppliers to improve supply chain performance. Drawing on a sample of 378 companies across Europe, North America, and South America, the study emphasized that elements such as visibility (real-time information exchange between buyers and suppliers) and integration (collaborative decision-making and execution of supply chain processes) hold greater importance than the technologies themselves do.

In regard to fostering collaborative practices for implementing I4.0 technologies, startups play a pivotal role. The evolving landscape of entrepreneurship, particularly shaped by the transitions from the impact of I3.0 and further enhanced within the realm of I4.0, has garnered significant attention in recent studies. Malerba and McKelvey (2020) introduce the concept of "knowledge-intensive innovative entrepreneurship" to describe a category of innovative, knowledge-driven new ventures. These startups establish connections with key players within innovation systems and seek opportunities across various sectors. Within the context of I4.0, there exists a niche of small companies that distinguish themselves by both utilizing and offering new technologies (MÜLLER; BULIGA; VOIGT, 2018).

The advancements in I4.0 have also prompted shifts in public policies. Primarily, remarkable industrial policy initiatives are underway to bolster the growth and competitiveness of sectors. As highlighted in the work of Labrunie, Penna and Kupfer (2020, p. 32), there is a renewed focus on industrial policies:

> […] despite several idiosyncrasies, the main common justification for the strategies is the perception of technological opportunities and challenges, especially in new digital technologies. These are seen as opportunities not only for maintaining (or gaining) industrial competitiveness in an environment of increased international competition (the focus of China and the US), but also for solving grand societal challenges such as population ageing and climate change (focus of Germany, Japan, and UK), which in itself is a new phenomenon. State intervention is then justified as a means to seize these opportunities, as it is understood that the private sector alone is not capable of achieving the desired level of R&D investment, nor of accumulating the necessary capabilities for effective innovation. Emphasis is given to the fact that innovation today requires a new level of collaboration between academia, industry, and government (and sometimes even society), and between traditionally separated fields of knowledge.

Second, the digital transformation of economies raises new challenges that require governmental intervention, particularly in regulatory domains such as addressing the complexities of autonomous vehicles, genetic manipulation, and the use of AI in healthcare (SCHWAB, 2017; FILIPPUCCI et al., 2024). These factors and others are catalysts for changes in key stakeholders and the nature of relationships and networks within SSIs. As highlighted by Li et al. (2021) and Fu et al. (2021), the changes brought by I4.0 create opportunities for interaction among various stakeholders, blurring the boundaries within and between SSIs. Additionally, the diverse strategies adopted by firms in response to these changes potentially impact the dynamics and core characteristics of SSIs.

Another crucial aspect related to public policies is the unequal impact that I4.0 will have on countries and regions. Analysis of patent data pertaining to the five key I4.0 technologies examined by Lee and Lee (2021) reveals significant dominance by five nations: the United States (comprising 77.7% of the total), followed by South Korea (4.2%), China (2.6%), Germany (2.3%), and Taiwan (2.2%). This concentration remains relatively unchanged compared with patents related to I3.0, with an important shift being Japan's exclusion from the Top 5, replaced by China. While other countries emerge in the top 5 rankings based on specific technologies (such as England, Spain, and Ireland in AI and Japan in BD and CC), approximately 90% of patents across all technologies are dominated by these five nations. This scenario presents significant challenges for developing countries, particularly given the close timing between the two recent waves of technological advancements (LEE; MALERBA; PRIMI, 2020).

Lee, Malerba and Primi (2020), Ferraz et al. (2020), Brixner et al. (2020) and Filippucci et al. (2024) recognize the necessity for public policies focused on the dissemination of I4.0 technologies in developing nations, as the benefits are not inherently guaranteed, and their implementation is fraught with uncertainties, particularly in a rapidly evolving environment. When formulating these policies, Ferraz et al. (2020, p. 404) argued that "…the diversity of modes of adoption of DT [digital technologies] by firms means that the object of policies should not be only the most advanced digital solutions. More important is the fostering of upgrading processes while respecting the stage at which development firms are at."

The importance of state support for the digitalization of economies can also be highlighted on the basis of the results of a recent study prepared with data from 24,000 firms and 75 countries. This shows that the advancement of digitalization processes has strong impacts on economic resilience, as they have meant increases in revenue and jobs in recessive phases, including the pandemic period (COPESTAKE; STEFANIA; FURCERI, 2024).

Considering this broad review of the literature, the next section pays attention to studies that analyze the dissemination of I4.0 in the steel industry properly.

3. Diffusion of I4.0 in the steel industry: a non-exhaustive review of the literature

Neef, Hirzel and Arens (2018) investigate ongoing activities and outlooks regarding I4.0 in the European iron and steel industry through an analysis of research & development (R&D) projects and patents supplemented by a survey (with 48 completed questionnaires) and interviews (fourteen). Notably, 51% of the survey participants represented research institutions, 24% were from steel companies, 17% were from software suppliers, 6% were from hardware providers, and 2% were from other organizations, indicating that steelmakers accounted for only a quarter of the sample. The study concludes that all major players in the sector are actively involved in digitalization efforts, with significant support from public policies. One notable funding source is the Research Fund for Coal and Steel (RFCS), which has spearheaded approximately 145 R&D projects for digitizing the European steel industry, with an average budget of EUR 1.7 million. The implementation of these projects focuses primarily on prototype applications and demonstrations, with a limited number of commercially driven endeavors.

The authors observed that numerous projects classified under I4.0 principally focus on automation, incorporating elements such as sensors or data-driven process controls. However, there is a lack of information concerning the economic advantages derived from these projects. The anticipated advancements are particularly concentrated on enhancing process efficiency (via intelligent support systems for the workforce) and fostering the creation of novel business models. Furthermore, areas such as rolling and coating/finishing within the production process (from a technical standpoint) and customer interactions (from an organizational perspective) are predicted to reap substantial benefits from I4.0 initiatives (NEEF; HIRZEL; ARENS, 2018).

In their study, Neef, Hirzel and Arens (2018) identified the primary challenges confronting the European steel industry in adopting I4.0.

These challenges revolve around issues related to outdated equipment, uncertainties regarding job impacts, and concerns surrounding data protection and safety. The survey findings indicate that while there are technical hurdles, organizational obstacles are perceived as more critical. A significant concern is the shortage of skilled personnel, with 74% of respondents highlighting its importance, while many (61%) also express the importance of rapid payback requirements. Interestingly, the expected return on investments related to I4.0 was not investigated. In addition, a majority (51%) believe that the lack of certainty or information regarding the economic benefits of I4.0 is a crucial consideration.

The authors also pinpoint the key players driving the implementation of I4.0. Internal management typically takes the lead (79% of participants), with technological departments (45%) and external suppliers (38%) playing supporting roles. Notably, "steel manufacturers often look to external expertise and collaborations with external partners when adopting I4.0 solutions" (NEEF; HIRZEL; ARENS, 2018, p. 23). This collaborative approach underscores the importance of comprehending the mechanisms influencing innovation within the steel industry.

Alacero (ASOCIACIÓN LATINOAMERICANA DEL ACERO, 2020) conducted an extensive survey involving 16 Latin American steel companies, which collectively represented 59% of the regional crude steel production in 2019. Importantly, the sample exclusively comprised steelmakers located in Brazil, Mexico, Argentina, Colombia, Peru, Chile, Ecuador, and the Dominican Republic. In terms of technology adoption, the utilization rates of various technological clusters were led by CC (94%), with system integration and cybersecurity following closely behind at 81% each. The survey also revealed adoption rates of 69% for IoT, 63% for robotics, 56% for BD/analytics, and 38% for simulators, augmented reality, and artificial vision, whereas additive manufacturing usage was 19%.

While companies recognize BD/analytics, robotics, and the IoT as the technologies that provide the most value to their operations, only one area within these companies currently integrates these technologies.

Interestingly, 83% of enterprises without existing BD implementations have plans to invest in this technology within the following two years. A similar trend is observed for robotics, with 80% of companies without current robotics applications planning to adopt them in the next two years. Among the areas within firms, the highest rates of I4.0 diffusion were observed in the rolling mill (transformation of crude steel into steel products), reduction (primary iron production), and steel shop (crude steel fabrication) - essential phases within a steel mill. While the environment and safety initiatives also represent an area of investment, they are on a smaller scale than the aforementioned key technologies are (ASOCIACIÓN LATINOAMERICANA DEL ACERO, 2020).

Latin American steelmakers highlight several key benefits resulting from I4.0 implementation, including cost reduction, increased productivity, and enhanced product quality (88% each). They also emphasize the standardization of operational practices and information organization (63%), process security and decision-making support (19% each), and data security (13%). To further expand the utilization of I4.0 and address associated challenges, professionals identified awareness and training as critical factors (94%). This is followed by the definition and investment in projects incorporating the technology, benchmarking with industry technologies (31% each), hiring a specialized team in I4.0 (19%), and forming partnerships with educational institutions for training purposes (13%) (ASOCIACIÓN LATINOAMERICANA DEL ACERO, 2020).

One way to expedite the implementation of I4.0 is through collaboration with technology providers, academic institutions, and startups. According to Alacero (ASOCIACIÓN LATINOAMERICANA DEL ACERO, 2020), 69% of participants have partnerships with academia, 32% with suppliers, and only 13% with startups. This indicates that there is room for increased collaboration in the steel innovation system within the I4.0 context, aligning with the insights from studies by Li et al. (2021) and Patrucco et al. (2022).

Gajdzik and Wolniak (2022) conducted a study on the implementation of I4.0 in the Polish steel industry. The research participants included employees holding managerial positions and involved in operating technological installations within steel sector enterprises. A total of 79 professionals took part in the research, representing companies categorized by size on the basis of the number of employees: very large enterprises employing over 500 people (20.3% of the total), large enterprises with staff ranging from 250-500 employees (36.7%), medium-sized companies with 50-250 employees (21.5%), and small companies with up to 50 employees (21.5%). The participants included representatives from the surveyed companies (middle management, employees in independent production roles, and operators of critical technologies) as well as industry experts (individuals with expertise combining scientific and industry functions).

The survey results analyzed the impact of I4.0 projects on enterprise operations using a scale from 1 to 5, with 1 indicating very low impact and 5 signifying the highest impact. The ranked categories were as follows: 1) quality and personalization: 90%; 2) speed and agility: 85%; 3) adaptability and work precision: 84%; 4) value and competitiveness: 77%; 5) productivity and management: 68%; 6) supply and cooperation: 66%; 7) flexibility and reliability: 54%; 8) profitability, and integration and block chain: 51% (each); 10) staff reduction and manual operation diminution: 46%; and 11) cost decrease: 27%. The surprising position of cost reduction at the bottom of the list was explained by the authors in the following manner: "The impact of SM [smart manufacturing] projects on cost reduction depends on the ROI [Return on Investment] of each project and the surveyed companies expect a decrease in production costs only after a comprehensive implementation of multiple, related projects that allow the companies to achieve a high level of smart maturity" (GAJDZIK; WOLNIAK, 2022, p. 10).

Another noteworthy finding regarding Poland's steel industry experience is that very large and large companies collectively rated the impact of I4.0 projects on operational enhancement significantly higher than medium and small firms did (GAJDZIK; WOLNIAK, 2022). This suggests that I4.0 tends to deliver more benefits to larger enterprises in an industry known for its economies of scale.

Numerous academic works have explored I4.0 in the steel sector, including the insightful book titled "I4.0 and the road to sustainable steelmaking in Europe: Recasting the future" (STROUD et al., 2024). However, this brief literature review focuses specifically on articles that predominantly investigate the diffusion of I4.0 technologies in the steel industry, mainly through quantitative analyses.

4. Methodological procedures

In 2021, we published an article titled "Technological innovations and industry 4.0 in the steel industry: Diffusion, market structure and intra-sectoral heterogeneity" (MARTINS; DE PAULA; BOTELHO, 2021). Both the 2021 article and the current one utilized the framework of "technological clusters" proposed by the "Indústria 2027" project (INSTITUTO EUVALDO LODI, 2017). These clusters encompass a collection of key technologies categorized by technological proximity and the knowledge bases they entail.

The 2021 article, which is based on data collected in 2018, arrived at several key conclusions: a) the diffusion of I4.0 technologies tends to increase operational efficiency and productivity incrementally rather than instigating a revolutionary shift, thus maintaining the minimum optimal scale of plants and specific equipment unchanged; b) the steel shop and rolling stages present the best opportunities for the application of these technologies, with the steel shop referring to the midstream phase and rolling to the downstream stage; and c) regarding market structure, technological clusters exhibit a bias toward established players rather than newcomers, primarily owing to the limited alterations in entry barrier intensity and nature. This underscores that I4.0, on a global scale and specifically in the Brazilian steel industry, is more about evolutionary advancements rather than revolutionary transformations.

The steel industry worldwide has an oligopolistic market structure, principally due to significant economies of scale. While this limited number of enterprises contributes to a representative sample, companies may have minimal incentives to take part in academic studies that involve lengthy questionnaires, as is the case with this research. The questionnaire, consisting of 19 questions and requiring input from various departments, was estimated to take approximately five hours to complete. Given the emerging and multifaceted nature of the theme, a questionnaire format was chosen for face-to-face interviews. A pilot test was conducted before the initial round of questionnaires; however, for this second application, a pilot test was not administered.

In the initial article, the sample consisted of six major steel mills in Brazil: ArcelorMittal Tubarão (AMT), Companhia Siderúrgica do Pecém (CSP), Gerdau, Ternium Brasil, Usiminas, and Vallourec. Collectively, these companies represented 82.8% of the country's crude steel production in 2018 (INSTITUTO AÇO BRASIL, 2019). The questionnaires were answered exclusively by steelmakers, mirroring the approach taken in Alacero (ASOCIACIÓN LATINOAMERICANA DEL ACERO, 2020). In addition to their production volume representation, these firms operate plants with equipment spanning different technological eras (including mills built from the 1960s to the 2010s), utilize diverse technological processes (some based on iron ore, others on scrap as primary inputs), and cater to various market segments (flat steels, long steels, and seamless tubes).

The sample of companies in the study has several advantages. Notably, these firms possessed substantial knowledge of global and national trends, with five having significant foreign ownership and one operating subsidiaries abroad. Additionally, the respondents who completed the questionnaire were IT professionals actively engaged in I4.0-related projects, holding pivotal corporate or technical management roles. Importantly, these respondents were typically selected by the company presidents, indicating that they are closely aligned with corporate strategies and directives.

Conducting a second round of questionnaires with the same sample of companies in late 2021 is a somewhat uncommon practice in economic research, primarily due to potential challenges such as companies declining to participate in a follow-up study or changes in ownership structures due to mergers and acquisitions. However, we were fortunate to secure responses from the same firms, enabling a comparison between the first and second data collections, which is one key aspect of this article. In addition to examining the diffusion level itself, our focus is on emphasizing the rate of evolution over a three-year period. Importantly, the second round of questionnaires took place during the COVID-19 pandemic. While the questions did not directly address the global health crisis, it is reasonable to assume that it may have indirectly influenced the companies' responses to some extent.

The macroeconomic conditions differed significantly between the two surveys, which clearly affected the questionnaire responses: GDP increased by 1.3% in 2017 compared with that in the previous year, whereas it declined by 3.3% in 2020 in comparison with that in 2019 due to the impacts of COVID-19. From a sectoral standpoint, the outcomes are more varied. On the one hand, crude steel production experienced a year-over-year increase of 9.9% in 2017 and a decrease of 3.5% in 2020. On the other hand, there were some consistencies: a) the apparent consumption of steel products in Brazil rose by 2.3% in 2017 and 2.0% in 2020, each time compared with the previous year; b) sectoral investments totaled USD 706 million in 2017 and USD 691 million in 2020 (INSTITUTO AÇO BRASIL, 2019, 2022). Therefore, despite the vastly different macroeconomic contexts, some crucial sectoral indicators remained relatively similar at the times the questionnaires were administered.

To compare how enterprises' perceptions of technological innovation diffusion changed over time, the questionnaires, although primarily similar, were expanded to 26 questions in the second round. An essential addition was a query aimed at understanding the expected return on investments associated with I4.0. This adjustment was made to address the relative scarcity of information on the economic benefits of implemented I4.0 projects, as noted by Neef, Hirzel and Arens (2018).

The questions posed to the interviewed companies, which were later synthesized and analyzed, were framed within the Neo-Schumpeterian/

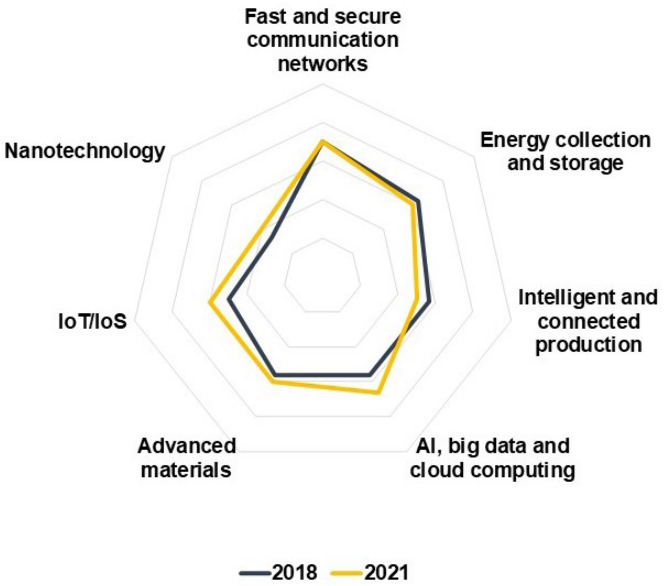
evolutionary approach. The key themes explored included a) the rate of technological diffusion and changes in technological trajectories (DOSI, 1988); b) technological dynamics and barriers to entry (DOSI, 1988; TEECE, 2010); c) increasing heterogeneity among companies (NELSON, 1991; COAD, 2019); and d) technological partnerships (MUSCIO; CIFFOLILLI, 2020). The questionnaire, which was already comprehensive, exclusively researched aspects related to I4.0, omitting other notable topics such as decarbonization, which falls outside the research scope but represents an emerging technological paradigm for the industry.

5. Analysis of results

The companies initially disclosed their current perceptions of the diffusion levels of technological clusters linked to I4.0. Each cluster was rated by the firms on a scale ranging from very low to too high. These subjective perceptions were then quantified via a conversion scale where very low perceptions corresponded to one, low to two, moderate to three, high to four, and too high to five, following a similar methodology that was employed by Alacero (ASOCIACIÓN LATINOAMERICANA DEL ACERO, 2020) and Gajdzik and Wolniak (2022). Graph 1 illustrates the perceived level of each technological cluster in both 2018 and 2021. Not surprisingly, the analysis reveals differences not only in the diffusion rates of the innovations but also in the speed of their evolution, as further elucidated below.

The fast and secure communication networks maintained the highest diffusion rates in both 2018 and 2021, at a moderate level, without significant improvement. Conversely, the most substantial advancements, indicative of the speed of evolution, were observed in AI, BD and CC, and IoT/ Internet of Service (IoS). Despite notable progress, these technologies still lag behind fast and secure communication networks in terms of dissemination. The notable progression of AI is particularly intriguing, especially considering that

GRAPH 1
Rhythm of the diffusion of technological clusters in the Brazilian steel industry, 2018 and 2021.



Source: Data compiled from surveys conducted with the participating companies.
Note: The intensity levels represented by the curves indicate the diffusion rhythm, with the progression from the center to the edge signifying very low, low, moderate, high, or too high.

our data collection occurred before 2023-2024, when generative AI gained global attention. McKinsey's assessment (MCKINSEY, 2023a, p. 4) sheds light on this transition: "But because AI has permeated our lives incrementally – through everything from the tech powering our smartphones to autonomous-driving features on cars to the tools retailers use to surprise and delight consumers – its progress was almost imperceptible". However, McKinsey highlighted that this scenario has changed dramatically. The consulting firm asserts that the era of generative AI, viewed as a catalyst for technological advancement, is just commencing.

Graph 1 also reveals that Brazilian steel companies perceived intelligent and connected production, as well as energy collection and storage, to have unexpectedly decreased in diffusion. While this outcome was not directly explained through the questionnaires, a few possibilities can be suggested: a) over time, companies may have gained a better understanding of the technological clusters, leading to a more accurate assessment; b) rapid advancements in global state-of-the-art technology could create a perception that domestic diffusion of these technologies is lower than expected; and c) despite having the same set of companies in the sample, different professionals with varying opinions may have been responsible for responding to the questionnaires.

Notably, nanotechnology exhibited the lowest diffusion rates in both 2018 and 2021. This establishes a clear hierarchy among technological clusters, which is particularly evident when the extremes are compared. However, when all the technological clusters were examined collectively, the overall dissemination ratio improved only modestly, lingering around the moderate level. Consequently, it can be inferred that the pace of I4.0 innovations has not accelerated as rapidly as anticipated. The Brazilian steel companies appeared to take a measured approach in expanding the diffusion of technological clusters, suggesting that the application of I4.0 in this sector may be more evolutionary than revolutionary. This observation aligns with previous studies that have highlighted the uneven adoption rates of I4.0 technologies across sectors and countries, with developing nations facing greater challenges (ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT, 2017; LEE; MALERBA; PRIMI, 2020).

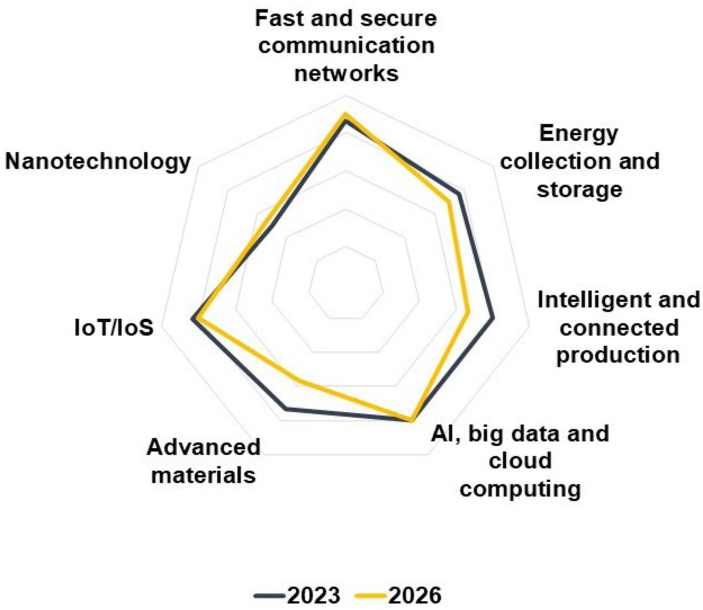
Interestingly, the slower pace of I4.0 innovations in the steel sector may be influenced by some inherent traditional characteristics of the industry's innovation system. As highlighted by Lee and Li (2017), the steel industry is often characterized by a lower frequency of innovation than other industries. This is attributed to the fact that many technological processes in the steel sector have been in use for decades, leading to a slower rate of technological change and innovation adoption. Soltanzadeh, Rahman and Majidpour (2024, p. 10) also stress the following:

> The essential characteristic of the steel industry regarding innovation development is its mature character, where technological advancement is scarce. Incremental advancement in process

innovation is crucial in modernizing the industry's technological foundation. This is evident in the fact that the most recent radical innovations in the steel sector, such as the development of basic oxygen, continuous casting, and electric arc furnaces, trace back to the 1950s and 1960s.

Graph 2 focuses on the anticipated future diffusion (five years ahead) of technological clusters within the Brazilian steel industry. Specifically, the data collected in 2018 sought forecasts for 2023, whereas the 2021 information pertained to 2026. Companies expressed optimism regarding the dissemination of fast and secure communication networks, which are expected to maintain their prominent position. Interestingly, nanotechnology, typically the least advanced, is the only other technological cluster anticipated to exhibit a higher dissemination ratio in 2026 than in 2023.

GRAPH 2
Rhythm of the expected diffusion of technological clusters in the Brazilian steel industry, 2023 and 2026.



Source: Data compiled from surveys conducted with the participating companies.

In Graph 2, AI, BD, and CC are projected to maintain their diffusion rates in 2026 compared with those in 2023. More importantly, the expected dissemination rates for other technological clusters, such as IoT/IoS, intelligent and connected production, energy collection and storage, and advanced materials, are predicted to be lower in 2026 than in 2023. This finding underscores the low traction (highlighting the slow adoption issue) of I4.0 within the Brazilian steel industry, at least as of 2021. Notably, the data were collected during the COVID-19 pandemic, which inevitably heightened macroeconomic uncertainty and negatively impacted enterprises' investment decisions.

Brazilian steel companies believe that the most critical technological trajectory related to I4.0 is cost reduction, scoring 4.7 out of 5.0. This emphasis is understandable given their status as commodity producers. They also consider production flexibility and significantly lower the environmental impact, each scoring 4.5 points. The development of new products (4.3 points) and the improvement of existing products (4.2 points) are also highlighted. Comparing these results with data from 2018, the focus on cost reduction has continued to dominate, followed by new product development and existing product improvements. However, there has been a significant shift in production flexibility and a lower environmental impact, which were previously noted in only one-third of the samples. Two hypotheses may explain this change: a) the increasing importance of environmental, social, and governance (ESG) issues and decarbonization in corporate discussions and b) a better understanding by companies of technological clusters and their impacts, particularly related to production flexibility. Despite this, the steel industry is traditionally seen as a continuous process business where cost reduction is vital for survival. Thus, I4.0 appears to reinforce this characteristic.

The findings of our research are consistent with those of PWC (PRICE WATERHOUSE COOPERS, 2016), who concluded that the most significant benefits that Brazilian companies expect from I4.0 include enhanced efficiency, cost reduction, and revenue growth. Additionally, McKinsey (2022) reported that, according to a survey of more than 400 companies globally, the top three motivations for adopting I4.0 are a) the ability to scale operations up or down to meet market demand changes; b) the flexibility to tailor products to consumer needs; and c) the enhancement of operational productivity and performance to reduce costs.

Regarding the SSI, the Brazilian steelmakers indicated that the primary sources of innovation for technologies related to I4.0 are as follows: a) machinery and equipment, scoring 4.7 out of 5.0; b) external knowledge, scoring 4.2; c) internal R&D, scoring 3.8; d) training, scoring 3.7; and e) external R&D, scoring 3.5. Machinery and equipment, along with external knowledge (primarily from universities and research institutes), continue to be the main sources of innovation. It is understood that training can be provided by consultant companies, among others. These rankings have remained consistent with data from 2018, reinforcing the historical reliance of steel companies on externally developed technologies (SILVA; CARVALHO, 2016) rather than modifying this characteristic.

In terms of learning mechanisms, the companies emphasized that intragroup interaction is the most important, with a score of 4.3 points. This is understandable given that all companies have operations or partners in other countries. They also highlighted R&D and interactions with universities and research institutes (each scoring 4.2 points), along with interactions with other companies (3.8) and subcontracting (3.5).

With respect to interactions with other firms, Brazilian steelmakers place the greatest importance on interactions with established foreign companies, scoring 4.3 points. This is followed by interactions with established Brazilian companies and Brazilian start-ups, each scoring 4.0 points, and finally, with foreign start-ups scoring 3.3 points. Given that I4.0 involves more risks than established technologies do and requires high capital intensity, the preference for well-proven suppliers highlights the dependence on foreign technology providers within the Brazilian steel industry.

New questions in the recent questionnaire addressed participation in innovation hubs and their relevance for I4.0 technological clusters.

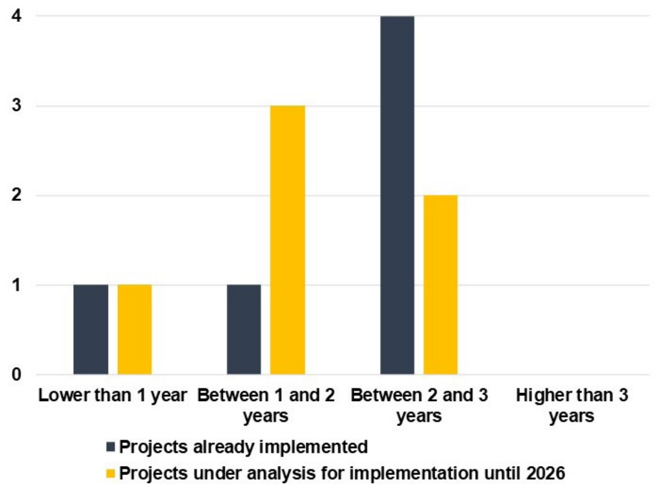
Innovation hubs are geographic concentrations of R&D institutions, tech-enabled corporations, universities, venture capital, incubators, and start-ups (MCKINSEY, 2023b). However, three out of six companies reported not participating in any technological hubs. For the three that do, the current importance rankings are led by IoT/IoS, AI, BD and CC, and intelligent and connected production, each scoring 3.7 points. They are followed by fast and secure communication networks at 3.3 points and energy collection and storage, as well as advanced materials, at 3.0 points. Nanotechnology scores the lowest at 2.7 points. Notably, the fast and secure communication networks did not rank first for the first time.

The relevance of innovation hubs for I4.0 by 2026 is expected to increase, especially for fast and secure communication networks and IoT/IoS, both of which are projected to score 4.7 points. AI, BD, and CC are expected to score 4.3 points; intelligent and connected production, at 4.0 points; and nanotechnology, energy collection and storage, and advanced materials, each at 3.0 points. Significantly, the hubs become more important for each technological cluster, which is an unforeseen result considering Graph 2. Brazilian steel companies appear to be increasingly inclined toward open innovation and intensive cooperation with start-ups, reaffirming the crucial role of start-ups in I4.0 (MÜLLER; BULIGA; VOIGT, 2018).

Contrary to the European experience (NEEF; HIRZEL; ARENS, 2018), Brazilian steelmakers indicated that current governmental support for I4.0 activities is low, scoring 2 points, and is expected to increase to 2.7 points by 2026. Despite this slight anticipated increase, this lack of robust government involvement is not unique to the steel industry in Brazil but contrasts with other countries where I4.0 technology implementation support has intensified in recent years (ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT, 2017; LABRUNIE; PENNA; KUPFER, 2020).

An important addition to the questionnaire was related to the financial outcomes of I4.0 investments. Regarding the predominant payback period for projects already implemented, four companies (two-thirds of the sample) reported time-to-return periods between two and three years, one company informed a payback period between one and two years, and one company answered a time-to-return period of up to one year (Graph 3). These figures are notably fast compared with typical productive investments conducted by steelmakers in Brazil and globally. However, this outcome is more pessimistic than general expectations: according to PWC (PRICE WATERHOUSE COOPERS, 2016), 63% of Brazilian firms and 55% of the global sample estimated that payback on I4.0 investments would occur within two years.

GRAPH 3
Payback of the I4.0 already implemented and under analysis investments.



Source: Data compiled from surveys conducted with the participating companies.

The Brazilian steel enterprises also provided insights into the expected predominant payback period for I4.0 projects being considered for implementation until 2026. Half of the sample (three companies) believe that the time-to-return will occur between one and two years, while two companies anticipate a payback period of between two and three years, and one company expects it to be less than one year. Notably, no company assumes a time-to-return period longer than three years. Interestingly, four companies assessed the time-to-return differently between past and future I4.0 investments. The prospect of a shorter planned payback period makes these investments even more appealing for an industry characterized by high capital intensity and long-term project maturation. As stated by the Energy Transitions Commission (2023, p. 8), this trend aligns with broader industry expectations and enhances the attractiveness of I4.0 initiatives: “Steelmaking is highly capital-intensive, requiring significant investment into assets with long life spans. While investors typically expect steel assets to pay back their up-front investment in 10 years or fewer, steel facilities can operate for decades”. Notably, steel plant installations have long lifetimes, typically involving 25-year investment cycles and average lifespans of approximately 40 years (INTERNATIONAL ENERGY AGENCY, 2020). In this context, I4.0 technological clusters can serve as valuable tools for optimizing existing facilities in the steel industry.

6. Conclusions

The debate on I4.0 primarily revolves around its diffusion, impacts, and nature. In our previous article published in 2021, Brazilian steel mills categorized the dissemination of technological clusters within the industry into three levels: a) very low: nanotechnology; b) low: IoT/IoS, AI/BD/CC, intelligent and connected production, advanced materials, energy collection and storage; and c) moderate: faster and secure communication networks.

Regarding impacts and nature, the mentioned article concluded that I4.0 technologies generally have not substantially changed the barriers to entry in the Brazilian steel industry but have significantly enhanced enterprise competitiveness. Specifically, these technologies tend to a) reinforce existing technological trajectories, with process development remaining under the purview of specialized suppliers while steel mills focus on product enhancement; b) be incremental rather than radical innovations, thus strengthening current technological routes rather than creating new ones; c) maintain the intensity and nature of barriers to entry, favoring established enterprises over potential newcomers; and d) widen the technological gap among steel mills, thereby benefiting the most innovative companies.

In this second round of questionnaires, which forms the basis of this article, we again focused on the degree of diffusion. Considering all the technological clusters combined, the dissemination ratio has improved marginally from that of the previous article, remaining at a moderate level. Importantly, having the same sample for both articles allowed us to analyze the evolutionary speed of each technological cluster, led by AI/BD/CC and IoT/IoS. However, surprisingly, Brazilian steel companies believe that intelligent and connected production and energy collection and storage have seen reduced diffusion. Thus, the pace of I4.0 innovations has not been as rapid as expected. In fact, Brazilian steelmakers seem not to be in a hurry position to amplify the diffusion of technological clusters, suggesting that I4.0 applications in this sector may be more evolutionary rather than revolutionary.

The impacts on the steel system of innovation thus far appear to be limited. Machinery, equipment, and external knowledge remain the primary sources of innovation, with no significant changes in their role compared with the previous article. For learning mechanisms, intragroup interaction is emphasized as the most important, which is understandable given that all companies have controlling shareholders or operations in other countries. Notably, the interviewed enterprises prefer interacting with consolidated suppliers (particularly foreign) rather than start-ups, reaffirming the reliance on foreign technology suppliers in the Brazilian steel industry. Additionally, half of the sample reported not participating in any technological hub but expected to increase their engagement by 2026. Furthermore, Brazilian steel companies seem more inclined to adopt open innovation and increase cooperation with start-ups in the future.

Regarding the financial outcomes of I4.0 investments, both the projects already implemented and those under analysis for completion by 2026 have payback periods faster than three years. This is notably good performance for an industry characterized by high capital intensity and substantial sunk costs associated with long-term investment cycles and long lifetimes.

This article aimed to contribute to the literature on innovation and the transformation of productive structures by presenting the technologies of I4.0 and their applications and implications for the Brazilian steel industry. On the one hand, the results indicate that the speed of diffusion of technological clusters in this sector has been relatively slow, and the implications for the steel system of innovation have been quite limited. On the other hand, the financial outcomes (measured by payback) have been very satisfactory. Therefore, such innovations can be effective tools (in terms of availability and financial returns) for optimizing the current productive structure rather than revolutionizing it.

Finally, the research presented in this article, which was conducted over two periods, generally confirms the findings of several studies summarized by Tigre and Cário (2023) in a special issue of RBI. Specifically, it highlights the slow pace of adoption of I4.0 technologies by Brazilian firms.

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