Revista Brasileira de Inovação
ISSN: 1677-2504
ISSN: 2178-2822
Universidade Estadual de Campinas

Martins, Mozart Santos; Paula, Germano Mendes de; Botelho, Marisa dos Reis A.

Technological Innovations and Industry 4.0 in the Steel Industry: Diffusion, Market Structure and Intra-Sectoral Geterogeneity

Revista Brasileira de Inovação, vol. 20, e021006, 2021
Universidade Estadual de Campinas

DOI: https://doi.org/10.20396/rbi.v20i00.8660896

Available in: https://www.redalyc.org/articulo.oa?id=641772410001

Revista Brasileira de Inovação
ISSN 2178-2822
DOI: https://doi.org/10.20396/rbi.v20i00.8660896

ARTICLE

Technological Innovations and Industry 4.0 in the Steel Industry: Diffusion, Market Structure and Intra-Sectoral Heterogeneity

* *Mozart Santos Martins*
Samarco Mineração SA, Belo Horizonte (MG), Brazil
E-mail: mozart.s.martins@gmail.com

** *Germano Mendes de Paula*
Universidade Federal de Uberlândia (UFU), Uberlândia (MG), Brazil
E-mail: germano@ufu.br

*** *Marisa dos Reis A. Botelho*
Universidade Federal de Uberlândia (UFU), Uberlândia (MG), Brazil
E-mail: botelhomr@ufu.br

Received: 17 August 2020 Revised version: 24 December 2020 Accepted: 03 April 2021

Abstract

Based on the Neo-Schumpeterian approach on technology and economic change, this paper proposes to evaluate the effects of the diffusion of Industry 4.0 technologies in terms of the technological dynamics, market structure and intra-sectoral heterogeneity within the Brazilian steel industry. In questionnaires answered by a representative group of companies it was observed that the Industry 4.0 technologies tend to incrementally improve the operational efficiency and productivity of the respective activity rather than revolutionize it, remaining unchanged the minimum optimal scale both of the plants and of the specific equipment. The results also show that the best opportunities for application of such technologies lie in the refining and rolling stages. Concerning the market structure, "technological clusters" tend to favor established companies, due to the lack of important changes to the intensity and nature of barriers to entry.

Keywords | Industry 4.0; Technological innovation; Brazilian steel industry

1. Introduction

Industry 4.0 (I4.0) refers to what would be a fourth industrial revolution, based mainly on digitization and interconnectivity of production chain systems and linkages. This allows a substantial increase in operational efficiency and the development of new business models, products and services.

The multidisciplinary nature of I4.0 requires the involvement of industry, suppliers, universities, research institutes, various organizations, and different levels of government. Thus, the main business challenges regarding the changes intrinsic to I4.0 have been faced with the participation of companies in collaborative networks and with the provision of public support (MUSCIO; CIFFOLILLI, 2020).

In the steel industry, the advance of innovations and the diffusion of new processes and technology, along with the increased interaction between suppliers, producers and users, tends to promote a deepening of the sectoral system of production and innovation. These opportunities for innovation and building of competitive advantages based on the developments of I4.0 focus on the incorporation of autonomous processes, with greater energy efficiency and lower greenhouse gas emissions, and the development of more sustainable materials and better performance in terms of customer's needs (PETERS *et al.*, 2016).

Since I4.0 refers to an industrial revolution, on the one hand, it is usually associated with disruptive innovations that lead to radical and rapid technological changes in production processes (BIGLIARDI *et al.,* 2020; PEREIRA, ROMEIRO, 2017). On the other hand, Enose and Ramachandran (2019) state that, although such changes can be considered revolutionary when analyzed in retrospect, the transformations will be gradual for most companies in real time, configuring an evolution rather than a revolution. Asadollahi-Yazdi *et al.* (2020) also claim that I4.0 is an evolution of industry due to the development of various technologies. This article derives from the debate on the supposed disruptive nature of I4.0. Specifically, this paper aims is to evaluate the effects of the diffusion of I4.0 technologies regarding technological dynamics, market structure and intra-sectoral heterogeneity of the Brazilian steel industry. The theoretical perspective adopted is Neo-Schumpeterian/ evolutionary one, whose developments support the understanding that the specificities of sectoral and national dynamics should be permanently objects of research (DOPFER; NELSON, 2018).

To fulfill this objective, questionnaires were distributed to a group of companies in the sector, with a significant share of the industrial production and a substantial

knowledge about global and national trends, either because they are subsidiaries of foreign companies or because they have investment abroad.

The article is organized into six sections. After the introduction, the second section presents the theoretical framework that supports this study. The third section points the main technological developments in the steel industry and empirical cases of applications and results achieved by the steel mills regarding the incorporation of the development of I4.0. The fourth section describes the methodological procedures and the fifth discusses the key results obtained by the research. Finally, the last section summarizes the main conclusions.

2. Theoretical foundations

The growing diffusion of the information and communication technological paradigm has been stimulating the development of increasingly intensive and knowledge-dependent business models. Amidst this transformative environment, the dissemination of *Big Data,* Internet of Things (IoT) and Advanced Materials technologies represents a series of efforts in the evolution towards more efficient systems and processes. In this context, the concepts of technological paradigms and trajectories gain relevance, due to the important milestones for understanding the role of innovations in the shaping of market structures and in the process of structural change and in the active role of firms in directing these transformations.

In the seminal reference for the evolutionary theory of technological change (NELSON; WINTER, 1982), Dosi (1988) proposes that a technological paradigm should be defined as a standard of solution of technical-economic problems, based on selective principles derived from the natural sciences, together with specific rules for the acquisition of new knowledge and mechanisms of protection against its rapid diffusion among competitors. In a recent study, G. Dosi and R. Nelson state that "[…] *when they are basically held in common by those knowledgeable about the technology, these bodies of practice, knowledge, and approaches to advancing the state of the art together defines what might be called a 'technological paradigm*[…]" (DOSI; NELSON, 2018, p. 57).

Within the framework of a new paradigm, technological trajectories influence the direction of technological progress and the solution of technical and economic trade-offs, which will be pursued by innovative firms. The companies' ability to innovate will be directly related to their previous efforts to accumulate technological knowledge and, therefore, delineating a path dependency process. High levels of

technological accumulation within the firm favor established companies and elevate barriers to entry, whereas low levels indicate that relevant knowledge is disseminated, stimulating the entry of new competitors, thus contesting the positions of incumbents. The ability of innovative firms to protect imitative innovation – patents, industrial secrecy, etc. – comprise the conditions for the appropriability of innovation.

The differences in the knowledge base, innovation sources, and appropriability conditions constitute the basis of Pavitt's taxonomy (1984). This paper discusses the sectoral differences of the innovative process, especially the relative importance of product and process innovations, the sources of process technology, and the size and pattern of technological diversification of innovative firms. The sectors were initially classified as: a) dominated by suppliers; b) intensive in production, subdivided into large-scale producers and suppliers of specialized inputs; c) science intensive. This contribution stimulated a fertile academic discussion that culminated in a further development proposed by the author (BELL; PAVITT, 1993), by incorporating the information-intensive sectors into the four aforementioned types, or even by raising new taxonomies, such as those of Castellacci (2008) and Bogliacino and Pianta (2016). These studies propose to integrate industrial and service activities, to consider recent trends of inter-sectoral articulations, which have been deepened by I4.0.

Based also on the evolutionary theory of technical change, Malerba (2002, 2006) develops the concept of sectoral systems of innovation. According to this approach, the types and structures of relationship and the networks of firms differ considerably from one sectoral system to another, due to the characteristics of the knowledge base, learning processes, basic technologies, demand characteristics, the main links and dynamic complements. At the sectoral level, this approach emphasizes the issues of institutional complexity and diversity that characterize innovative activities, as first addressed by Nelson and Winter (1982) and, later, by in-depth studies by evolutionary economists, analyzed in Dosi and Nelson (2018). Such contributions point out important differences in the roles of companies, universities, governments, and other public and private organizations in innovative sectoral activities.

Despite these differences, the literature that develops or uses the Schumpeterian competition approach focuses on the firm as the main agent of the innovative activity. In this field of studies, the significant differences between companies are pointed, among others, in size, growth rates and strategies, especially those involving innovations, which can have disruptive effects on market structures (DOSI; NELSON, 2018). Given the relevant differences in innovative behavior,

even for firms operating in the same sector, taxonomies should be viewed with caution regarding their explanatory value (ARCHIBUGI, 2001; COAD, 2019).

In a context of technical change, either with the emergence of new paradigms, or by means of a solution of technical-economic trade-offs (incremental innovations), the survival and growth of firms will depend on the possession of resources and training, built over time. Teece and Pisano (1994) develop the notion of dynamic capabilities, a term that, according to the authors, expresses the ability to respond to rapid changes in the environment, by the key strategic role of management to adapt, integrate and reconfigure internal and external organizational skills, resources and functional competencies towards the changes.

The different strategies undertaken by the firms, or their heterogeneity, correspond to different organizational structures and skills, including innovating skills. Consequently, companies will follow different trajectories from each other and achieve diverse success rates. These organizational differences, especially regarding the skills to innovate and make profits from innovations, are more than similarities within the domain of certain technologies, they are the crucial long-term sources – and difficult to replicate – differences among companies (TEECE, 2010; NELSON, 1991).

In short, differences between sectors and firms within the same sector are founding elements of the evolutionary theory of technological change. In more recent studies, Winter (2017), Dosi and Nelson (2018) and Dopfer and Nelson (2018) reinforce the importance of the theory initially proposed by Nelson and Winter (1982) and its first contributions (DOSI, 1982; 1988; MALERBA, 2002, 2006; PAVITT, 1984; TEECE; PISANO, 1994). These are the main references that guide the empirical study that comprise the core of this article.

3. Steel, Innovation and Industry 4.0

3.1 Main features of technological change in steel

The economic activities involved with the generation of new products and processes in the steel industry are close to basic science and specialized equipment suppliers, especially the metallurgical equipment industry and microelectronics, as noted in Pavitt's pioneering studies (1984) and later contributions (HOLLEIS, 1994; PINHO, 2001; DE PAULA, 2012).

Both in the Pavitt's taxonomy (1984), and in the most recent reclassifications made by Castellacci (2008) and by Bogliacino and Pianta (2016) to incorporate

service sectors, the steel industry is classified within the scale intensive sectors. As main characteristics, one can highlight the strong presence of production engineering departments and R&D expenses, both internal and from suppliers, as main sources of innovation and technical progress. In fact, in the study by Castellacci (2008), which presents a methodology more appropriate to the discussion of recent interaction between industry and services, the industry of machinery and equipment for the steel industry is classified as "advanced knowledge providers". On the industry side, manufacturers of precision machinery, equipment and instruments and, through services, are identified by the so-called "knowledge-intensive business services".

Advances in the knowledge of how innovations develop in the steel industry emphasize its mature industry character, in which technological ruptures are rare and incremental process innovations are relevant to the modernization of the technological base. For example, the last three radical innovations in the sector (the development of basic oxygen steel shop, continuous casting and the greater diffusion of electric steel shop) date back to the 1950s and 1960s. Therefore, there is a low degree of opportunity for innovation, resulting from the exploration of some technological trajectories that have been dominant for several decades. Pinho (2001) points out that the main technological innovations of the steel process were developed in initiatives that combined the efforts and capabilities of steel mills, equipment producers and public research institutes.

De Paula (2012) points out that, historically, steel companies have dedicated an increasing share of R&D spending to new products, relegating efforts to develop process technologies for engineering companies and equipment manufacturers. This is a consequence of the higher appropriability derived from product innovations rather than from steel processes. These conditions tend to induce a shyer technological strategy from steel enterprises. This is reflected in the low intensity of R&D spending in the steel industry, compared to other technologically more dynamic industrial sectors, thus reinforcing the conditions of technological maturity of the industry under analysis. Silva and Carvalho (2016) show that, over the period from 1995 to 2009, the R&D intensity of the steel industry was relatively low when compared with the average of the manufacturing industry, in countries such as Germany, Sweden, South Korea and Japan. In the case of the Japanese steel industry, situated on the technological frontier of the world steel industry, the intensity of R&D/sales in the steel industry (iron and steel manufacturing) was 3.8%, compared to 12.3% of the manufacturing industry as whole. Lee and Ki (2017) also point out that steel has a low frequency of innovation compared to other industries, since many of its

technological processes have been used for decades. Nakamura and Ohashi (2012) emphasize the relevance of learning in the steel industry.

Besides, according to Silva and Carvalho (2016), two aspects regarding the patenting activity must be emphasized, which reflects the conditions of appropriability of innovations: a) both in absolute and relative terms, investments favor nobler steels (galvanized and alloyed steels), which are products of high added value; b) of the 100 companies that most require patents related to steel, 90% were non-steel firms, reinforcing the predominance of technologies externally developed. In fact, the most relevant innovations end up being incorporated into equipment, which makes its diffusion dependent on large investments in fixed capital.

It can be argued that steel industry is mature, and innovations developed by steel mills and from operational practice (in products, in production organization and, to a lesser extent, in processes) are a fundamental feature of technical progress in this activity. Moreover, steel equipment suppliers represent the central element in the development of process technologies, whereas steel mills are primarily committed to product innovations.

3.2 The diffusion of Industry 4.0 technologies in the global steel industry

Industry 4.0 has become the technological theme of the moment, whether in developed economies or in emerging countries, although still little treated in the academic sphere, even in advanced nations (MUSCIO; CIFFOLILLI, 2020). Although these innovations are diffusing more rapidly in high-tech industries, as expected, they are also being implemented in more mature sectors (such as steel), but at a more cautious pace. This is largely explained by the fact that the steel industry is already very automated and has already collected, stored and analyzed data from its production processes for many years.

According to Pinkham (2018), many of I4.0 core technologies are not new. For example, machine learning algorithms, which improve the ability to recognize data patterns and use them in the decision-making process have existed for several years. The novelty is the change in the perception of the importance about the I4.0 concepts by the steel mills, in particular the understanding that the data are very valuable and that these could be better utilized to improve the production processes.

Collecting and analyzing this data became easier with the development of these technologies, allowing a better understanding of the process. According to Peters (2017), the main implications of I4.0 for steel industry are:

- Single plant as a Cyber Physical Production System (CPPS, vertical integration);
- Full traceability of intermediate and final products;
- "Intelligent" product with knowledge of its own quality and production history (one aspect of end-to-end engineering);
- Intensive Network and communication of all plants (horizontal integration inside company);
- Intensive communication along the complete supply chain (horizontal integration outside company);
- Suitable handling and usage of all data;
- De-central instead of central solutions (self-organization).

In this context, steel mills seek specific solutions that allow them to function as digitized factories, a necessary condition to achieve the benefits of the "I4.0/Smart Plant" (PETERS, 2017; PINKHAM, 2018). According to Peters *et al.* (2016) and Peters (2017), the greatest impacts of I4.0 for the global steel industry refer more to operational efficiency than to the change of *modus operandi,* comprehending the following advantages: a) decision support regarding quality control; b) smart control of process chain (through-process automation); c) smart evaluation of large amounts of data; d) re-scheduling of materials; e) smart assistance systems (drones, for example); f) smart (predictive) maintenance.

Regarding data collection and the efficient use of information generated during the production process, the development of technologies that enable a higher level of connectivity through machine-to-machine (M2M) networks and intelligent data analysis stands out. Another critical point in the steel industry refers to the management of maintenance and assets in general. Because it is a continuous process, unscheduled interruptions to repair or replace components due to breakage imply a high cost. In the event that spare parts are not available in inventories or on a rapid delivery basis, a break-in may result even to stop the plant (WINTER *et al.*, 2018). To solve this problem, machine learning and predictive maintenance are used to predict when a mechanical device will wear out or break (ALACERO, 2018; WINTER *et al.*, 2018).

Although they are in the initial state, some steel mills – both new and already established – have begun to incorporate the concepts of I4.0. Kinch (2017) describes an interesting experience of the Posco Institute (linked to the largest South Korean steel company of the same name), in partnership with the Department of Systems Management Engineering of Sungkyunkwan University, in the combined use of Artificial Intelligence and Big Data. The main benefits were: a) automation of the

control of the high oven by means of deep learning; b) implementation of precision deformation control through Big Data in the thick plate rolling mill; c) use of sensors to measure the concentration of gas in the reheating oven of the hot strip rolling mill; d) quality of galvanized sheets and reduction of zinc consumption. According to De Paula (2017), the experience of the Posco Institute reinforces technological trajectories more associated to the optimization of existing processes than to the disrupted factors. Moreover, such innovations tend to provide good financial returns because the need for investments is relatively low for the industry standards, whereas the payback to obtain results is relatively short.

In the scope of greenfield investments, Big River Steel, located in the United States, is perhaps the most emblematic case today, although the effects cannot be credited exclusively to the I4.0 technologies. This company has opted for a single supplier for all plant equipment and electrical and automation systems to overcome the problems of configuration of interfaces and poor performance when the systems of different providers do not communicate properly. In addition, the entire process chain of the plant is digitally mapped by more than 50,000 sensors, by which 3 to 4 terabytes of data are monitored and collected monthly (MPT INTERNATIONAL, 2017; ADJOGBLE, 2018). According to De Paula (2017), Big River Steel's experience shows that innovations have provided high productivity and high yield of steel processes and lower environmental impact when compared with plants with the same production technology, besides a rapid ramp-up.

Even with the numerous advantages of technologies, Pinkham (2018) points out that the current demand of steel mills for IoT is low. This is partly because most of the IoT platforms are not yet mature and mainly because the steel makers are reluctant to share data. There is a great concern in implementing the new technologies, especially regarding data security, including the amount of information that companies want to expose to the external environment. Cyberattacks, which have become increasingly frequent, would be the biggest distress of steel makers.

De Paula (2017) cites two attacks on steel mills. The first case occurred in 2014, when Germany's Federal Office of Information Security reported in its annual report a cyberattack on a steel mill, which would have caused physical damage by preventing the perfect operation of the blast furnace. The second episode occurred in 2016, when ThyssenKrupp publicly acknowledged that commercial technical secrets were stolen from its steel division, but it has not mentioned the specific impacted sites or speculate about probable suspects. It is in this context of many possibilities of innovation, but with significant obstacles, that the questionnaires were applied to Brazilian steel mills.

4. Methodological procedures

This article has adopted the same framework of "technological clusters" proposed by the "Indústria 2027" project (IEL, 2017) and in studies published under the scope of this project was adopted, as showed in Chart 1. These clusters comprise a set of key technologies grouped by technological proximity and knowledge bases involved. An electronic questionnaire was chosen, instead of a face-to-face interview, since the theme is emerging and involves several corporate areas. In the first stage of the research, a pilot test was conducted with the steel company ArcelorMittal Tubarão (AMT) between June and August 2018, to verify the compliance of the questionnaire to the objectives of the study. After the necessary adjustments, the definitive questionnaire was forwarded to the other consulted companies. In a second stage, contacts were made via telephone and/or e-mail to confirm the information provided and clarify relevant points. This stage ended in 2018, whereas data processing was prepared throughout 2019.

The sample comprises six large steel mills: AMT; Companhia Siderúrgica do Pecém (CSP); Gerdau; Ternium Brasil; Usiminas; and Vallourec. The companies consulted accounted, together, for 82.8% of the Brazilian crude steel production in 2018 (IABr, 2019). Besides the representativeness regarding the volume of production, a set of enterprises have production plants that incorporate equipment from different technological eras and serve different market segments. Moreover, they are firms with high knowledge of global and national trends, five of which have relevant foreign ownership and one has subsidiaries abroad. It is also worth mentioning that the interviewees are professionals in the area of Information Technology (IT) directly involved with work plans related to I4.0, and occupy corporate or technical management positions. It is important to emphasize that respondents were generally chosen by the presidents of the companies, suggesting that they are well aligned with corporate guidelines.

The questions directed to the companies interviewed, synthesized and analyzed in the next section were constructed according to the Neo-Schumpeterian/evolutionary approach. The main themes covered were: a) the pace of technological diffusion and changes in technological trajectories (DOSI, 1988); b) the technological dynamics and barriers to entry (DOSI, 1988; TEECE, 2010); c) the expansion of heterogeneity among companies (NELSON, 1991; COAD, 2019); d) the technological partnerships (MUSCIO; CIFFOLILLI, 2020).

CHART 1
Industry 4.0's Technological Clusters

Technological Clusters	Key Technologies	Definition
Artificial Intelligence Big Data and Cloud Computing	Artificial Intelligence	Ability of computerized machines to perform tasks typically associated with beings endowed with intelligence.
	Big Data	Set of computational techniques and tools used in the extraction of value of large volumes of data.
	Cloud Computing	Data transfer and performance of computational processes in facilities external to the firm and subsequent recovery of data and results through the Internet.
Fast and Secure Communication Networks	Computer system, distribution channels and resources for information exchange	Layer model with the objective of separating the different functions involved in information traffic - physical network and control logic.
Internet of Things (IoT) and Services (IoS)	IoT	Interconnection system, through the Internet or a specific network, of digital devices embedded in everyday objects, allowing them to send and receive data and act on these objects.
	IoS	Digital means by which companies, people or intelligent systems can communicate with the purpose of providing and obtaining services.
Intelligent and Connected Production	Own technologies and associated technologies	Use of interconnected cyber-physical systems (CPS), digitization, processing and optimization of the production chain, with increasing use of Artificial Intelligence.
Advanced Materials	Scientific and technological advances	Advances in traditional materials, encompassing new or modified materials with performance, structural or functional, superior in one or more critical characteristics for its commercial application.
Nanotechnology	Scientific and technological advances	Development of nanoscience and nanotechnology, areas of science and technology that deal with matter on the nanoscopic scale and apply the concepts and materials produced from these advances.
Energy Collection and Storage	New materials, nanotechnology and biotechnology.	Electrochemical Energy Storage Processes (ES or EES), through the use of a chemical reaction (redox reaction) to store energy, as well as the set of techniques and mechanisms that seek to harness small amounts of energy from physical and mechanical processes or the environment, transforming them into useful energy (Energy Harvesting)

Fonte: IEL (2017). Own elaboration

The questionnaires, which were already relatively extensive, addressed exclusively aspects related to I4.0. Therefore, no other important aspects were examined, since they went beyond the scope of the research, such as the low-carbon economy (which can be understood with a new technological paradigm for the industry), the influences on the total volume of investments (which are greatly influenced by macroeconomic factors and the level of utilization of the installed capacity of each company) or the propensity to export (which is affected by the level of investments itself , but also by the trade policy of the countries).

5. Analysis of results

The results were divided into four blocks to facilitate the understanding and interaction between the themes. Initially, the possibilities of applications of technologies and, then, the perception of the current and prospective diffusion in the Brazilian steel industry are discussed. Subsequently, the technological strategies of the companies consulted, the expected influences on barriers to entry and the main technological partnerships are presented. For confidentiality reasons, the results are addressed together.

5.1 Applications of Industry Technologies 4.0

In the perception of the consulted steel mills, the clusters technologically related to I4.0 present a range of applications, but with varied intensities according to the stage of the production process.

The steel production process can be divided into four stages: load preparation, reduction, refining, and rolling mill. The stage of preparation of the cargo aims to benefit the inputs (coal and iron ore, mainly) that will be used in the next step, aiming at a better operational performance of blast-furnaces.

In this first stage, with the exception of those related to Advanced Materials and the Nanotechnology, all technologies can be applied more intensively. In the raw material yard, IoT has been used in the monitoring of mobile people and machines through Radio Frequency Identification (RFID) technology, monitoring of vehicles via ground penetration radar (GPRs) and monitoring of equipment and processes using wireless sensors (vibration, temperature, pressure, etc.). In general, these sensors aim to collect and record information about the dimensioning of raw materials and control interactions with the external environment (human-machine).

Fast and Secure Communication Networks (hereinafter "Networks") are responsible for transporting the data generated to the various expert systems, for example, the Manufacturing Execution System (MES). Moreover, the implementation of networks with high communication capacity has enabled image traffic to video analytics functionalities, allowing the analysis of the production process in real time. Regarding the application of Artificial Intelligence/Big Data/Cloud Computing, this is restricted only to the first technology, a phenomenon that is not exclusive to this stage of the steel process. According to De Paula (2017), this fact occurs for two reasons: a) the current diffusion of these technologies in the world steel industry is low; b) the application of Artificial Intelligence occurs in a disjointed way with the other two technologies. Therefore, Artificial Intelligence has been used in specialist sintering/pelletizing systems, such as soft sensor (online chemical analysis of the sinter) and blending (homogenization of raw materials), and in decision making in the process of unloading materials, such as better route, discharge times and material need.

The Intelligent and Connected Production cluster, in general, reflects the application of the technologies mentioned above, including acquisition of equipment with embedded intelligence and automatism in general, and integration of information with suppliers. Energy Collection and Storage technologies seek to reduce energy consumption through recovery or utilization, mainly via the use of thermal processes and/or generation of coke oven gases.

In the reduction process, the blast-furnace is responsible for transforming iron ore into pig iron. In this stage I4.0 technologies mentioned above have been applied, and can even be used more widely. The implementation of sensors in blast-furnaces seeks to increase the efficiency of these equipment and optimize maintenance activities (predictive and corrective ones). The intensity of use of Advanced Materials in the reduction stage may become more relevant, due to the challenges associated with the growing difficulties in obtaining quality raw materials.

The refining process transforms metal inputs (pig iron and scrap, mainly) into steel (in the steelmaking departments) and its subsequent cooling (in casting). Various equipment can be incorporated in this stage, depending on the steel to be manufactured. Thus, the best opportunities for technological and energy innovations associated with I4.0 are in the refining stage. The manufacture of products of greater complexity, aiming to meet the needs of the environment and customers (customization), mainly by lighter and more resistant materials, provides the use of composites associated with Nanotechnology, reinforcing the development of new products, which has been the predominant strategy of steel mills.

The cluster Artificial Intelligence/Big Data/Cloud Computing tends to provide significant benefits, especially regarding predictive manufacturing, making the interface between maintenance and predictive quality associated with intelligent planning in real time. Thus, numerous initiatives have been observed in the refining stage, among them: a) the implementation of sensors to optimize maintenance and increase the efficiency of equipment; b) the application of artificial neural networks for prediction and control of parameters of steel production in converters, with the objective of controlling the final temperature of leaking and chemical composition; c) availability of liquid steel production information to regulate the speed/quantity of production in downstream steps; d) the addition of special metal alloys in the composition of steel to meet specific physical metallurgical properties.

Rolling mill is the step aiming to transform steel into a marketable product for industrial and final consumers. As in the refining process, different types of equipment are also used at this stage according to the product to be manufactured. Thus, the opportunities are concentrated in the informational content embedded in the final products, allowing cost reduction, either by the best final quality of the product or by reducing downtime per equipment stop.

Regarding the use of IoT, best practices focus on using sensors for process monitoring, such as reheating ovens; hot rolling mills; cold rolling mills; trowels; cutting and finishing lines. Automation networks for process interconnection, with emphasis on Industrial Ethernet, make up Network Technologies. In turn, the use of artificial neural networks to predict physical properties in rolling mill processes stands out in the use of Artificial Intelligence. Together, these technologies seek to drive the Intelligent and Connected Production cluster by expanding information connections with suppliers and customers. The clusters with the lowest effect of use in this stage are Advanced Materials, Nanotechnology and Energy Collection and Storage.

Generally speaking, despite the trend of a cost reduction, which in itself represents an incentive for their adoption, most of these technologies are still being tested and, in some respects, need to evolve to gain the necessary robustness for industrial processes. Even in this scenario, the consulted firms envision that the effects of technological clusters will be more intensive in the stages of refining and rolling mill. This is a consequence of the fact that a greater control of processes in these steps can provide cost reductions, both related to predictive maintenance and the greater efficiency of equipment and raw materials. That is, in both stages are the best opportunities to improve the operational efficiency and productivity of steel mills.

5.2 Dissemination of Industry Technologies 4.0

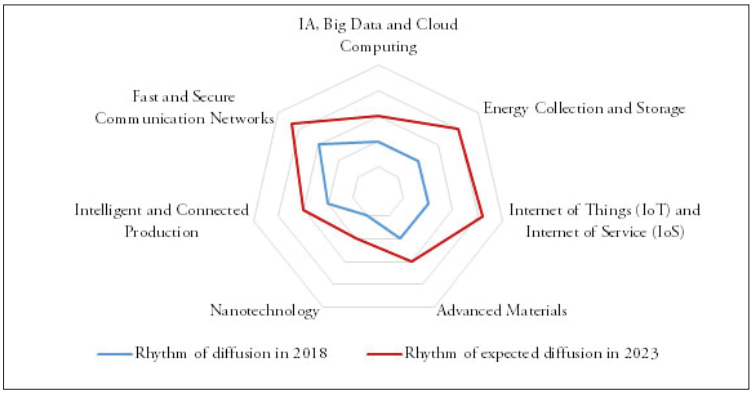
In the perception of the consulted companies, the current diffusion of clusters IoT/IoS, Artificial Intelligence/Big Data/Cloud Computing, Intelligent and Connected Production, Advanced Materials and Energy Collection and Storage in the Brazilian steel industry is low. On the other hand, Network Technology has a moderate diffusion rate, whereas the dissemination of Nanotechnology is incipient (very low). The results corroborate the view of Brazilian steel mills regarding the diffusion of technological clusters in the world steel industry. Based on De Paula (2017), also according to the perception of Brazilian steel mills, the diffusion of IoT clusters, Artificial Intelligence/Big Data/Cloud Computing, Intelligent and Connected Production, Advanced Materials and Energy Collection and Storage in the world steel industry is low, while for Network Technologies, dissemination is moderate. The diffusion rate of the Nanotechnology cluster in the world steel industry is low, whereas the use of this technology is still incipient (very low) in the Brazilian steel industry. Therefore, with the exception of the Nanotechnology cluster, the rate of diffusion of I4.0 technologies in the Brazilian steel industry is similar to that of the world steel industry.

The consulted companies believe that the technical and/or economic barriers are directly related to the current rate of diffusion, namely: a) the financial return of projects, since the relationship proving the use versus benefits is not always tangible before their application; b) the absence of government incentives, especially for the acquisition of machinery and equipment with embedded technology; c) the regional condition of Latin America, with low levels of professional qualification, which requires the training of people in some of these technologies; d) the educational institutions with an inadequate curriculum relating to the challenges of I4.0, demanding high educational investment to obtain satisfactory results. To the extent that these challenges are overcome, the intensity of use of these technologies tends to increase. The development of digital technology ecosystems and the evolution of hardware in the coming years will expand the offer of developers of specific applications, resulting in a use versus benefit relationship more attractive to investments associated with I4.0.

That said, the expectation of the steel mills consulted is that, in 2023, the clusters Artificial Intelligence/Big Data/Cloud Computing, Intelligent and Connected Production and Advanced Materials will present a moderate diffusion in the Brazilian steel industry, whereas the diffusion of IoT/IoS, Networks and Energy Collection and

Storage will be high, while Nanotechnology continues with low diffusion. Graph 1 summarizes the predominant perception about the diffusion of clusters in Brazilian steel sector in two-time horizons: in 2018 and 2023.

GRAPH 1
Rhythm of diffusion of Technological Clusters in the Brazilian steel industry, 2018 and 2023



Source: Own elaboration from the companies consulted.
Note: The curves of levels represent the intensity of the diffusion rhythm, interpreted from the center to the edge as: very low; low; moderate; high; too high.

Regarding the expected rate of diffusion for the country's steel industry in 2023, the results found show some divergences related to the perception of the same Brazilian steel mills regarding the diffusion rate in the world steel industry. While for the latter, the expected diffusion rate for Advanced Materials will be low, the consulted companies expect a moderate pace in Brazil. In turn, for the IoT and Energy Collection and Storage clusters, the expected spread to the world steel industry is moderate and low, respectively, whereas a high diffusion of both clusters is waited for the Brazilian steel industry.

The sample used is identical to that of De Paula (2017). Although the results found are similar regarding the current diffusion rate, the same does not occur for the rhythm of future dissemination of the clusters investigated. The short time between the two papers and the divergence of results is indicative of the great dynamism and, at the same time, of the high level of uncertainty regarding the rate of diffusion of new technologies in this production chain.

5.3 Technological dynamics, barriers to entry and heterogeneity

The development of these technologies and the better understanding of their complications in the production process tend to improve the operational efficiency and productivity of steel mills. Its increased dissemination will allow for a wide capacity of data processing and analysis, eliminating redundant events, inefficient tasks or unwanted interfaces in processes. These opportunities should represent an advantage in the industry, which is still heterogeneous. Thus, the use of these technologies can become differentiating and competitive factors between companies.

However, so far, no significant changes are envisaged in the minimum production scale of specific plants or equipment. In fact, the new technologies do not change the size of the steel shop equipment and, consequently, the minimum productive batch. As one of the consulted companies states, "equipment with higher levels of sensing and automation tend to better suit the required productivity levels".

The prevailing view is that clusters tend to favor established companies without substantial changes in barriers to entry. Three of the six consulted firms believe that established steel mills are the most favored by I4.0 technologies. One of them declares:

> *If we consider the opportunity to create action of new greenfield plants, they can already come with these embedded technologies and gain a competitive differential for some aspects. But when talking about the quality of products associated with the conditions of their processing and the conditions of the equipment, in a plant where there is a good level of instrumentation, control and optimization, with history of their data and information, this can be a significant competitive differential for plants already in operation.*

In turn, two steelmakers believe that I.40 clusters tend to benefit innovative companies, regardless of whether they are incumbents or entrants. Only one mentions that new technologies tend to favor the entry of new competitors, although it did not provide further information. The predominant perception corroborates the degree of technological maturity of the steel industry, and the main barriers for the entrants are in the initial volume of capital, in the sunk costs and in the tacit knowledge of steel processes. This reflects the importance of incremental innovations for the technological dynamics of the sector, which have contributed to the improvements of steel equipment and products in recent decades. Although the installation of new production plants by new entrants can add the new technologies, the resulting

advantages seem to be insufficient to overcome the benefits for established firms in detaining crucial information about production processes. This fact is extremely relevant when it comes to product quality, especially in complex processes.

The way each company evaluates new technologies and their benefits, believes in these technologies and invests, varies according to its objectives, which is in line with the propositions of the evolutionary theory of technological change (NELSON; WINTER, 1982; DOSI; NELSON, 2018). The technological strategies of steel mills, in response to new challenges, tend to change the current distribution of enterprises, influencing on a greater heterogeneity among firms. In this sense, half of the sample believes that the technologies associated with I4.0 increase the heterogeneity in general (Chart 2).

CHART 2
Perception of companies with concerns about the expansion of heterogeneity among steel companies according to Industry 4.0

Number of companies	Heterogeneity between companies
3	Extends heterogeneity in general
1	It increases heterogeneity according to the segment of activity.
1	It expands the heterogeneity between Brazilian steel mills and the rest of the world.
1	Reduces heterogeneity in general.

Source: Own elaboration from the consulted companies.

For one of the consulted steel mills, the diffusion of technological clusters "will provide less heterogeneity, since conservative companies will be obliged to implement technologies already consolidated to maintain their competitiveness, whereas traditional companies will be obliged to follow innovative companies, developing new processes and products". On the other hand, for another steelmaker, the heterogeneity "will be higher in the case of producers of special steels in general and coated flat rolled steel and smaller in most common long steels, which have the characteristic of maturity regarding the standard pattern of innovation that prevails in the Brazilian steel industry". Finally, one company points out that:

> *The fact that large technology providers are outside Brazil and, at the same time, are making associations with government programs, specialized equipment suppliers and end customers, added to the initiative of large steel companies to incorporate*

specific units focused on technology and innovation in their productive structures, tend to increase heterogeneity between Brazilian steel mills and their competitors.

In general, the heterogeneity between firms is a reflection of the different strategies, which, in turn, correspond to different organizational structures and skills, including the ability to innovate (NELSON, 1991; TEECE; PISANO, 1994; TEECE, 2010). Consequently, steel mills will follow different technological trajectories from each other under I4.0 umbrella that bring relevant effects for the innovation appropriability.

5.4 Technology partnerships for Industry 4.0

The requirement of equipment with a higher level of sensing, automation and Artificial Intelligence capacities tends to reinforce the importance of specialized equipment suppliers in the steel sector, although, as in other sectors, partnerships with technology companies can accelerate the use of the mentioned clusters, by technological solutions adapted to the production process of each company. Despite the interactions between steel producers, steel equipment suppliers and service providers tend to intensify and influence the sectoral system of innovations, so far, no drastic changes are envisaged in the innovative steel process.

The predominant technological partnerships point to the importance of interactions with universities, technology suppliers for steel and suppliers of digital technology in search of technological solutions adhering to the reality of Brazilian steel companies (Chart 3). This result is consistent with those obtained by Muscio and Ciffolilli (2020) who, when analyzing the process of integration between I4.0 technologies in Europe, emphasized the importance of partnerships in research projects, interregional collaboration and public funding funds. In the case of the interviewed companies, the collaborative technological strategies adopted differ considerably.

In general, new technologies tend to affect the entire steel production chain, from organizational management to the introduction of new products, which requires greater inter-organizational collaboration (MUSCIO; CIFFOLILLI, 2020) and engagement in the development of dynamic capabilities (TEECE; PISANO, 1994; TEECE, 2010). In fact, in the case of the intensity of technological change, the innovative process in the steel industry can become more dynamic; however, its characteristics (high investments and barriers to exit) discouraged this possibility.

That is, the nature and direction of these changes tend to reinforce the current technological trajectories, based on incremental process improvement and product enhancement.

CHART 3
Main technological partnerships according to the steel mills consulted

Number of companies	Technology partnerships
2	Partnerships with universities and digital technology providers.
1	Partnerships with universities and private institutions to foster innovation.
1	Partnerships with universities, private and public institutions to foster innovation and suppliers in general.
1	No formal partnerships, but pointed out the importance of entering into agreements with universities/research institutes and digital technology providers.
1	Uninformed.

Source: Own elaboration from the consulted companies.

Moreover, the innovations of I4.0, at first sight, reinforce the current characteristics of steel industry. New technologies open up endless possibilities to increase productivity, mainly because they require relatively low investments against the technological standard of the sector. However, in the current scenario, the competition patterns and the intensity and nature of the barriers to enter in the steel industry tend to remain unchanged.

6. Conclusions

Based on the Neo-Schumpeterian approach, this work evaluated the effects of the diffusion of I4.0 technologies in terms of the technological dynamics, market structure and intra-sectoral heterogeneity regarding the Brazilian steel industry. For such purpose, questionnaires were applied to a representative sample of the sector.

First, I4.0 technologies, in general, do not substantially modify the barriers to entry into the Brazilian steel industry, but contribute significantly to increase the competitiveness of companies in this industry. In fact, these technologies tend to reinforce the technological trajectories in the steel industry: the development of

processes tends to remain under the responsibility of specialized suppliers, whereas steel mills tend to continue directing their efforts towards the products enhancement. It should be emphasized that the main barriers to entrants are in the high production scales, in the high initial investment (and in the sunk costs) and in the tacit knowledge of steel processes.

The prevailing view of consulted steel firms is that technologies associated with I4.0 tend to favor established companies, without relevant changes in intensity and nature of barriers to entry. Even when the implementation of new plants was considered by part of potential competitors, the conclusion remained the same. This reinforces the relevance of accumulated knowledge about steel processes as an important competitive differential and high investments in fixed capital.

Concerning the view of steel mills about the application of new technologies in the production process, they believe that the reduction and refining steps are more likely to incorporate a greater number of clusters. The refining stage (steel shop and casting) is the only phase of the production process that can benefit from all the clusters investigated, whereas the reduction stage would not benefit only from Nanotechnology. On the other hand, the applications in the stages of preparation of inputs and rolling mill would be concentrated in some I4.0 fields. Moreover, the steel mills envision that the effects of clusters will be more intense in the stages of refining and rolling mill, since greater control of processes in these stages can result in cost reductions related to predictive maintenance and greater efficiency of equipment and raw materials.

Regarding the current rate of diffusion in the Brazilian steel industry, the interviewed steel mills believe that the clusters can be divided into three levels: a) Very Low: Nanotechnology; b) Low: IoT/IoS, Artificial Intelligence/Big Data/Cloud Computing, Intelligent and Connected Production, Advanced Materials, Energy Collection and Storage; c) Moderate: Networks. These results converge with the view of the same Brazilian steel companies about the current diffusion rate in the world steel industry.

Regarding the expected diffusion rate in the country for 2023, the results showed some divergence among the perceptions of Brazilian steel companies regarding the dissemination rhythm in the world steel industry. Whereas for the latter the expected diffusion rate for Advanced Materials is low, the consulted companies expect a moderate pace in the Brazilian steel industry. In turn, for the IoT/IoS, Energy Collection and Storage clusters, the expected diffusion in the world steel industry

is moderate and low, respectively, although the interviewed steel mills expect a high diffusion rate in the Brazilian steel industry.

The predominant perception of the consulted firms is that the diffusion of I4.0 tends to increase heterogeneity in general. The technological gap among steel mills tends to be widened, thus favoring the most innovative companies. The relevant fact is that when considering the technological distance between Brazilian steel mills and some international steel mills, which are on the technological frontier, heterogeneity tends to be substantially expanded. Thus, Brazilian companies should be engaged in implementing I4.0 technologies, to reduce the expansion of this gap and remain competitive. For such purpose, technological partnerships become essential.

The main technological partnerships pointed out by the companies are being signed with universities and suppliers of digital technologies, with the main objective of finding technological solutions that are adhering to the reality of Brazilian steel mills. In general, these relationships play the role of understanding how new technologies can improve the efficiency of production processes and provide greater security to their implementation.

This article sought to contribute to the literature of innovation and transformation of productive structures, presenting the technologies of I4.0 and their applications and implications for the Brazilian steel industry. The results show that clusters tend more to improve operational efficiency and productivity rather than transform the industry. Moreover, the results indicate that Brazilian steel companies are concerned about implement the new technologies, but are still insecure about their benefits, especially because it is an emerging theme.

In conclusion, the greater diffusion of clusters aims more to optimize than to revolutionize the steel industry (worldwide and in Brazil). The development of a new technological paradigm is not envisaged, but the reinforcement of the current predominant trajectories, which confirms the proposition that "[…] conceived as pathways, technological trajectories tend to remain oriented in particular directions for long periods of time." (DOSI; NELSON, 2018, p. 60).

Although there is no reduction in barriers to entry, no change in market structure and technological dynamics, intra-sectoral heterogeneity and the advantages of more innovative technological strategies are expected to increase, with effects in terms of appropriability and greater engagement in the development of dynamic capabilities. Thus, although I4.0 is not revolutionary for the steel industry, that increase of technological efforts will produce an asymmetry in the level of competitive and technological status between companies.

Acknowledgements

The authors are grateful for the valuable contribution of the following specialists and companies in the preparation of this study: Cristiano de Lanna (Usiminas), Felipe Ramos (Ternium Brazil), José Luiz Lopes de Sousa (Gerdau), Flávio da Silva Almeida and José Martins de Oliveira (ArcelorMittal Tubarão), Marcelo Menezes (Vallourec Soluções Tubulares do Brasil) and Wilson de Souza Paulino (Companhia Siderúrgica do Pecém – CSP). Germano Mendes de Paula benefited from taking part in the "Indústria 2027" Project, which contributed to the formulation of this article. The authors are also grateful for the valuable suggestions of the anonymous peer reviewers, who contributed much to the improvement of quality, but exempted them from any remaining errors.

References

ADJOGBLE, F. *Big River Steel:* the world's first learning steel mill. USA: SMS Group Gmbh, 2018.

ALACERO – Asociación Latinoamericana Del Acero. Aplicaciones específicas de la manufactura digital en la industria del acero. *Revista Acero LatinoAmericano*, n. 567, marzo-abril, 2018.

ARCHIBUGI, D. Pavitt's taxonomy sixteen years on: A review article. *Economic Innovation and New Technology*, v. 10, p. 415-425, 2001.

ASADOLLAHI-YAZDI, E.; COUZON, P.; NGUYEN, N.Q.; OUAZENE, Y; YALAOUI, F. Industry 4.0: Revolution or evolution? *American Journal of Operations Research*, v. 10, n.6, p. 241-268,2020. https://doi.org/10.4236/ajor.2020.106014.

BELL, M.; PAVITT, K. Technological Accumulation and Industrial Growth: Contrast Between Developed and Developing Countries. *Industrial and Corporate Change*, v. 2, n. 2, p. 157-210, 1993. https://doi.org/10.1093/icc/2.2.157.

BIGLIARDI, B.; BOTTANI, E; CASELLA, G. Enabling technologies, application areas and impact of industry 4.0: a bibliographic analysis. *Procedia Manufacturing*, n. 42, p. 322-326, 2020. https://doi.org/10.1016/j.promfg.2020.02.086.

BOGLIACINO, F.; PIANTA, M. The Pavitt Taxonomy revisited: patterns of innovation in manufacturing and services. *Economia Politica*, v. 33, p. 153-180, 2016. https://doi.org/10.1007/s40888-016-0035-1.

CASTELLACCI, F. Technological paradigms, regimes and trajectories: Manufacturing and service industries in a new taxonomy of sectoral patterns of innovation. *Research Policy*, v. 37, n. 6-7, p. 978-994, 2008. https://doi.org/10.1016/j.respol.2008.03.011.

COAD, A. Persistent heterogeneity of R&D intensities within sectors: Evidence and policy implications. *Research Policy*, v. 48, n. 1, p. 37-50, 2019. https://doi.org/10.1016/j.respol.2018.07.018.

DE PAULA, G.M. *Economia de Baixo Carbono:* Avaliação de Impactos de Restrições e Perspectivas Tecnológicas – Siderurgia. Relatório Final. Ribeirão Preto: EBC – Núcleo de Estudos em Economia de Baixo Carbono, 2012.

DE PAULA, G.M. Nota Técnica do Sistema Produtivo Insumos Básicos e Foco Setorial Siderurgia. *Relatório do Projeto Indústria 2027:* Riscos e Oportunidades para o Brasil Diante de Inovações Disruptivas. Rio de Janeiro: IE-UFRJ; Campinas: IE-Unicamp, 2017.

DOPFER, K.; NELSON, R. The Evolution of Evolutionary Economics. *In*: NELSON, R. *et al.* (ed.). *Modern Evolutionary Economics*. Cambridge: Cambridge University Press, 2018. p. 221-219.

DOSI, G. Technological Paradigms and Technological Trajectories: A suggeste interpretation of the determinants and directions of technical change. *Research Policy*, v. 11, p. 147-162, 1982. https://doi.org/10.1016/0048-7333(82)90016-6

DOSI, G. Sources, Procedures and Microeconomic Effects of Innovation. *Journal of Economic Literature*, v. 26, n. 3, p. 1.120-1.171, Sept 1988.

DOSI, G.; NELSON, R. Technological Advance as an Evolutionary Process. *In*: NELSON, R. *et al.* (ed.). *Modern Evolutionary Economics*. Cambridge: Cambridge University Press, 2018. p. 35-73.

ENOSE, N; RAMACHANDRAN, S. *Industry 4.0 as an evolution, not a revolution*. Dallas: Infosys Knowledge Institute, 2019.

HOLLEIS, G. Global trends in the iron and steel industry. *La Revue de Métallurgie – CIT,* v. 91, n.1, p. 145-160, 1994. https://doi.org/10.1051/metal/199491010145IABr. *Anuário Estatístico* (vários anos). Rio de Janeiro: Instituto Aço Brasil, 2019.

IEL/NC. *Mapa de clusters tecnológicos e tecnologias relevantes para competitividade de sistemas produtivos*. Brasília, DF: Instituto Euvaldo Lodi, Núcleo Central, 2017.

KINCH, D. Artificial Intelligence in steel: mills embrace big data, robotics. *Metals Insight*, v.12, n.14, 2017.

LEE, K; KI, J-H. Rise of latecomers and catch-up cycles in the world steel industry. *Research Policy*, v. 46, n. 2, p. 365-375, 2017. http://dx.doi.org/10.1016/j.respol.2016.09.010.

MALERBA, F. Sectoral System of Innovation and Production. *Research Policy*, v. 31, n. 2, p. 247-264, 2002. https://doi.org/10.1016/S0048-7333(01)00139-1.

MALERBA, F. Sectoral Systems: how and why innovation differs across sectors. *In*: FARBERGER, J.; MOWERY, D.C.; NELSON, R. (org.). *The Oxford Handbook of Innovation.* Oxford: Oxford University Press, 2006. p. 380-406.

MPT INTERNATIONAL. Big River Steel's flat steel complex on its way to become a learning steel mill. *Mettalurgical Plant and Technology (MPT – International)*, v. 6, p. 41-45, 2017.

MUSCIO, A.; CIFFOLILLI, A. What drives the capacity to integrate Industry 4.0 technologies? Evidence from European R&D projects. *Economics of Innovation and New Technology*, v. 29, n. 2, p. 169-183, 2020. https://doi.org/10.1080/10438599.2019.1597413.

NAKAMURA, T; OHASHI; H. Intra-plant diffusion of new technology: Role of productivity in the study of steel refining furnaces. *Research Policy*, v. 41, n. 4, p. 770-779, 2012. https://doi.org/10.1016/j.respol.2011.11.002.

NELSON, R.R. Why do firms differ, and how does it matter? *Strategic Management Journal*, v. 12, n. 2, p. 61-74, Winter 1991. Special issue. https://doi.org/10.1002/smj.4250121006.

NELSON, R.R.; WINTER, S. G.*An evolutionary theory of economic change*. Cambridge: Harvard University Press, 1982. 437p.

PAVITT, K. Sectorial patterns of technical change: towards a taxonomy and a theory. *Research Policy*, v. 13, n. 6, p. 343-373, 1984.

PEREIRA, A.C.; ROMERO, F. A review of the meanings and the implications of the Industry 4.0 concept. *Procedia Manufacturing*, v. 13, p. 1.206-1.214, 2017. https://doi.org/10.1016/j.promfg.2017.09.032.

PETERS, H.; BRUMMAYER, M.; CHUST, R.; COLLA, V.; GAILLY, E.; DELSING, J.; KÄMPER, F.; KUIPER, G.; KRAUTH, P. J.; MATHIS, G.; MOUTON, S.; PIETROSANTI, C.; SANFILIPPO, F.; WINTER, G. *Roadmap of integrated intelligent manufacturing in steel industry*. Brussels: European Steel Technology Platform (ESTEP), 2016.

PETERS, H. *How could Industry 4.0 transform the steel industry?* Future Steel Forum. Warsaw: Steel Times International, 2017.

PINHO, M. *Reestruturação produtiva e inserção internacional da siderurgia brasileira*. Tese (Doutorado) – Instituto de Economia, Universidade Estadual de Campinas, Campinas, 2001.

PINKHAM, M. Digital Technologies increase momentum. *Metal Market Magazine*, June, 2018.

SILVA, F.; CARVALHO, A. *Research and development, innovation and productivity growth in the steel sector*. Paris: Organisation for Economic Co-operation and Development (OECD), 2016.

TEECE, D. Technological innovation and the Theory of the Firm: the role of enterprise-level knowledge, complementarities, and (dynamic) capabilities. *In*: HALL, B.; ROSEMBERG, N. (ed.). *Handbooks of the Economics of Innovation.* North Holland, 2010. v. 1. p. 680-730.

TEECE, D.; PISANO, G. The dynamic capabilities of firms: an introduction. *Industrial and Corporate Change*, v. 3, n. 3, p. 537-556, 1994. https://doi.org/10.1093/icc/3.3.537-a.

WINTER, S. Pursuing the evolutionary agenda in economics and management research. *Cambridge Journal of Economics*, v. 41, n. 3, p. 721-747, 2017. https://doi.org/10.1093/cje/bex009.

WINTER, G.; KURKA, G.; ANKERMANN, K.; BINDER, A.; RINGHOFER, M. *The digital transformation of steel production*. Primetals Technologies Austria, 2018.

Authors' contributions:

A. Literature review and problematization: Mozart Santos Martins, Germano Mendes de Paula, Marisa dos Reis A. Botelho

B. Data collection and statistical analysis: Mozart Santos Martins, Germano Mendes de Paula

C. Preparation of figures and tables: Mozart Santos Martins, Germano Mendes de Paula

D. Manuscript development: Mozart Santos Martins, Germano Mendes de Paula, Marisa dos Reis A. Botelho

E. Bibliography selection: Mozart Santos Martins, Germano Mendes de Paula, Marisa dos Reis A. Botelho

Conflicts of interest: The authors declare that there is no conflict of interest.

Funding: Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), process n# 310723/2018-3.