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Changes in the steel chain in Industry 4.0. Some results of survey on the Polish steel market

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Abstract
The paper discusses the changes occurring in the steel industry and related markets as they move towards Industry 4.0. With significant investments in new technologies, steel mills are creating a smart environment for cooperation between producers, distributors, and consumers of steel products. The influence of Industry 4.0 within mills is being transferred to other participants in the steel product chains, and vice versa. The research aimed to determine the impact of Industry 4.0 technologies on the steel product chains in the Polish steel market. The research was conducted in Poland. The obtained database comprised 208 respondents (company executives), including steel mills and steel product manufacturers. Technologies (the pillars of Industry 4.0) are grouped into five technological fields: automation and robotics; warehouse automation; Computer systems, systems integration, mobile technologies, Big Data and IIoT, Blockchain and cybersecurity. Analysis was realized in the three respondent segments representing the steel chain in Poland [RSs]: Producer [P], Distributor [D], and Consumer [C]. The results of the research can help companies improve their steel product chains. The study takes a value chain approach, considering steel production, distribution of steel products, and services for orders and consumers of steel and steel products.

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1. Introduction

After the transformation of the Polish economy in the 1990s, from a centrally controlled economy to a market economy, the Polish steel market has gone through a long road of changes, starting from the privatization of state-owned enterprises and repair restructuring with foreign capital to modern steel mills that can compete with other producers in the global steel market (Gajdzik, 2014).

On the modern transformation path, the steel mills and dependent markets meet the European industrial policy and new technologies of Industry 4.0 (Herman et al., 2015; Kagermann et al., 2013; Schwab, 2016). Strongly popularised, the concept of Industry 4.0, by politicians, business people, academics, practitioners, and market analysts, several pillars of technological and organizational change emerged, which needed stronger digitization and automation of processes than before (Kagermann, 2015; Branca et al., 2020). Key changes are classified as the nine pillars of Industry 4.0: IoT, systems integration, simulation, augmented reality, big data, additive manufacture, autonomous system, cloud computing, and cybersecurity (Burell, 2019; Erboz, 2017Dubey et al., 2022; Senn, 2020). The idea of Industry 4.0 is "smart", according to S. Dais (2014) and J. Davis (2012) , these are high technologies co-creating cyber-physical reality with artificial intelligence (AI), which are brought into companies across steel product chains to create smart processes and smart products. "Smart" defines the manufacturer, as a "smart factory", with manufacturing processes, of the "smart manufacturing" type, smart enter chains, and creates smart chains, as well as the whole industry, which can be smart through the technologies of the Fourth Industrial Revolution. Although, after the COVID-19 pandemic of 2020, when many economies are in crisis, it is more difficult to implement technologies of Industry 4.0, industrial development is still transforming towards digitized processes and personalized products (Spieske and Birkel, 2021). In the economic crisis, the idea of Industry 4.0 has been encapsulated with values, in the next conception of industrial development, called Industry 5.0 (Grabowska et al., 2022; Gajdzik, 2022).

Already in the title of the European document, from January 2021, the European Commission (Industry 5.0, 2021) conveyed the key values of sustainable industry, people at the center of technological change, and business resilience to liability. The Polish steel industry, as part of the European steel industry, pursues development programs in line with internal and external policies. The steel market is constantly changing (Gajdzik and Wolniak, 2021), and its participants (main players: steel mills with distribution centers for steel products with fully automated warehouses) are changing processes to meet the requirements of steel consumers (the main markets for steel mills are the automotive and construction markets) through interoperable and intelligent technologies in steel chains.

The research gap that this paper addresses is the lack of empirical studies on the impact of Industry 4.0 technologies on the steel supply chain in Poland. The authors highlight that while there is a growing interest in Industry 4.0 and its potential benefits for various industries, including the steel industry, there is limited research specifically focused on the steel supply chain in Poland.

Planning research described in the paper we tried to find the research gap on the basis of the literature analysis. We analyze empirical studies about the implementation of Industry 4.0 technologies in supply chain especially in steel industry. In the analyzed literature we spot some researches being conducted in domestic markets, e.g. L. Kohnová and N. Salajová (2023) carried out research on the impact of Industry 4.0 on companies from a value chain model perspective in the Czech Republic and Slovakia. A study by Nagy et al. (2018) examined the impact of Industry 4.0 on value chain business strategy development. The authors found that Hungarian companies using CPS, CPPS and Big Data technologies have higher logistics service levels, more efficient processes, higher financial and market performance and are more competitive. Hungarian companies also emphasise systematic analysis of the data they generate. In the next period, the survey respondents plan to invest in IoT. The survey also found that optimising production processes is a fundamental aspect of achieving optimal production and economies of scale (Nagy et al., 2018). Even the creator of the value chain diagram himself - M.E. Porter (Porter, 1985; Porter, 1990) - was convinced that chains are changing and need to be studied in order to develop new value chain models. Industry 4.0 is changing value chains (Porter, 1985; Porter, 1990; Porter and Heppelmann , 2014; Ribeiro, 2019; Yuanqin et al., 2022; Hokey, 2010; Queiroz et al., 2020). Interesting aspects of Industry 4.0 implementation in Poland were presented by R. Miśkiewicz (2019). The research about implementation of Industry 4.0 in SME Sector was in-deep described by Ingaldi and Ulewicz (2020). The aspect of implementation of Industry 4.0 in Polish steel industry was analyzed by Niekurzak and Kubińska-Jabcoń (2021) and in European Commission documents (Murri, et al. 2021; Neef et al., 2018. After our analysis of the scientific literature we observe lack of the studies about relations between industry 4.0 and supply chain in steel industry.

The paper aims to fill this research gap by investigating the influence of various technological factors related to Industry 4.0 on the development of the steel supply chain in Poland. It examines the impact of automation and robotics, warehouse automation, computer systems and mobile technologies, big data and the Industrial Internet of Things (IIoT), and blockchain and cybersecurity on the steel chain. The authors use a questionnaire-based survey to collect data from different segments of the steel chain, including steel producers, distributors, and consumers.

By presenting the research results and assessing the perceptions of industry stakeholders, the paper contributes to understanding the importance and potential benefits of Industry 4.0 technologies in the steel supply chain context. It provides insights into how these technologies are perceived and their impact on various aspects of the steel chain in Poland.

The paper used such terms: as steel chain, steel product chain, value chain, and supply chain to describe the links between steel producers and markets.

2. Background of research

2.1. The concept of value chain in Industry 4.0

Over the past few decades, the concept of the value chain has evolved (Donovan et al., 2015). Although the concept of the value chain has evolved over the last few decades, it is currently in the midst of the biggest industrial revolution - the fourth revolution, which is based on digitality (the result of the third revolution) and Industry 4.0 technologies. Cyber-physical product manufacturing systems are changing value chains. Before the introduction of modern technologies, activities in the value chain were carried out by humans (manual) and verbal communication. The first wave of computerisation took place in the 1960s and 1970s, resulting in the automation of some value chain activities, such as order processing, invoice payment and computer-aided operations. The second wave of transformation took place in the 1980s and 1990s, when the Internet entered the market, enabling ubiquitous connectivity. Thanks to the Internet, activities were coordinated and integrated, which was reflected in cooperation with external suppliers, customers and other countries. and other countries. These two waves have led to many innovations in chains (Kohnova and Salajova, 2023; Porter, 2014). It all started with manufacturing according to the requirements of the Industry 4.0 concept.

Industry 4.0 is a result of the Fourth Industrial Revolution but it is an evolution of the industry coming through the development of several technologies (Asadollahi-Yazdi et al., 2020). According to Calabrese et al. (2020), Industry 4.0 represents an ‘evolution’ in factory operations and a potential ‘revolution’ in the manufacturers’ value proposition. Digitization of processes and IoT, Sensor Networks, Open Data on the Web, etc. have a strong potential to reorganize value chain streams and core. How, then, can companies take advantage of the opportunities associated with Industry 4.0 technologies to improve product chains? This question is being asked by many companies that have identified Industry 4.0 as a strategic direction for their businesses.

A value chain is a sequence of processes undertaken by companies for the market. The chain is made up of many companies that are producers, suppliers, and customers (we are talking about the industrial chain). The chain involves different services to customers. According to M.E. Porter (1990), a value chain consists of activities that an organization performs to deliver a valuable product or service to the market. A value chain is made up of a series of subsystems each with inputs, transformation processes, and outputs. In Industry 4.0, the value chains have IoT, Big Data, Data Analytics, embedded sensors, robots with great autonomy and flexibility, advanced manufacturing techniques (e.g. 3D printing), smart products and devices that can communicate and interact with each other (Porter, 2014). Potentially Industry 4.0 may bring about a change from isolated manufacturing activities to automated, optimized, and fully-integrated product and data flow within (global) value chains (Zuchella, 2017). Industry 4.0 organizes suppliers, manufacturers, and customers in a virtual, vertically, and horizontally integrated, value chain (Nagy et al., 2018; Stock and Seliger, 2016). Under the powerfully popularised concept of Industry 4.0, the steel industry cannot stand still. Steel producers, together with other value chain participants build value chains using Industry 4.0 technologies.

2.2. Digital transformation

Digital transformation has great potential to reorganise the chain and change the materiality of its elements. Digital transformation is reinforced in Industry 4.0 by new technologies that improve chains, e.g. IoT, blockchain, AI. Digital transformation actually allows each element of the value chain to be streamlined (Dastbaz et al., 2019). In sourcing logistics, digitalisation primarily supports procurement optimisation. Thanks to technology, companies can analyse price fluctuations in raw material markets much more accurately, allowing them to make more economical transactions. In distribution logistics, modern technology makes it possible to search for the most efficient distribution channels and analyse their future efficiency (thanks to predictive analytics, among other things). In the sales process, digital sales channels and the reliance on digital experience, i.e. the customer's experience in the digital environment (e.g. when shopping online), are growing in popularity (Kohnova and Salajova, 2023; Porter, 1990). Porter and Heppelmann (2014) state that new activities such as product data analytics and product safety have emerged in the value chain. Fundamental changes in marketing activities are also taking place in Industry 4.0. The most important of these changes are (Shkurupskaya and Litovchenko, 2016): the acceleration of the dissemination of commercial information through the use of new technological capabilities of marketing communication channels; the trend towards the dominance of virtual tools in promoting the comprehensive structure of integrated marketing communication; the ability to more accurately measure the economic efficiency of integrated marketing communication by monitoring digital data on consumers; the interactive nature of the relationship with consumers with the possibility of targeting and/or customisation directly at the place and time set using IoT applications; the new principles of cooperation in the "producer-consumer" chain, the reduction of indirect links and the increase of online and direct customer links with technologies e.g. at the product design stage.

Digital transformation is influencing the overall redesign of organisations. Technology builds vision across the value chain and underpins automation to ensure efficiency and competitiveness. When building a business strategy, an organisation must therefore consider the alignment of digital and IT systems. Indeed, depending on the company's profile and the type of products it offers, the company can use digital customer service, augmented and virtual reality or elements of predictive analytics, among others. The result is not only an improvement in the experience of the current customer, but also a handful of data that can be used to improve the purchase path of subsequent buyers. Industry 4.0 applications make it possible to observe the chain's processes in real time, and the combination of machines, products and people allows for a very fast, efficient and fully automated response to any change in the chain. Total transparency is ensured throughout the chain, making it much easier to optimise decision-making processes (Pereira and Romero, 2017). Industry 4.0 technologies provide the opportunity to respond flexibly to disruptions and failures in the chains. implementing a two-speed systems/data architecture - this will allow rapid action cycles to be differentiated from mission-critical applications with longer lead times (Müller et al., 2018).

In practice, the model of value chain is more multi-stage and more developed. In modern companies, the role of innovation is growing significantly (Gajdzik, 2022). Companies are still focused on improving production and related processes to reduce costs and increase productivity (BCG, 2015). Steel producers, strong corporate groups, who are leaders in the global steel market, started to build smart manufacturing a few years after the emergence of the Industry 4.0 concept. Their technological investments are being made with a strong connection to the needs and expectations of their customer markets, in particular the expectations of the automotive and construction sectors. So the value chain in the steel sector is becoming increasingly smart. The first stage of change was the digitization of the business and the automation of steel production (Gajdziik and Wolniak, 2021). Implemented automation, initiated robotics, improved predictive analytics, and digital process simulation (digital twin) allow steel mills to significantly influence production efficiency. Steel production technologies (EAF, BOF) are moving in the direction of decreasing resource and energy consumption (Gajdzik and Sroka, 2021; Flues et al., 2015; Johansson, 2015).

2.3. Industry 4.0 in steel industry

In the last years, the steel industry has witnessed significant changes and advancements in the context of Industry 4.0 (Antonazzo et al., 2023; Straat et al., 2022; Zhao et al., 2022). Especially the adoption of automation and robotics in steel production processes has increased. Steel manufacturers are leveraging advanced robotics and automated systems for tasks such as material handling, welding, and quality control. Robots are being employed in hazardous environments and performing repetitive tasks, resulting in improved efficiency, reduced labor costs, and enhanced worker safety (Atatreh et al., 2023; Hu et al., 2023).

Also Internet of Things technology has gained prominence in the steel industry, enabling the collection and analysis of real-time data from various production processes and equipment. By integrating IoT devices, sensors, and data analytics, steel companies can monitor and optimize production parameters, predict equipment failures, and implement preventive maintenance strategies. This leads to enhanced productivity, reduced downtime, and better resource utilization (Xu et al., 2023; Kuhahamed and Rajak, 2023; Rankhi et al., 2023).

With the increasing availability of data from various sources in the steel industry, there has been a growing focus on harnessing the power of big data analytics. Steel manufacturers are utilizing advanced analytics tools and algorithms to extract insights from large datasets. These insights help in improving production planning, optimizing inventory management, identifying quality issues, and enhancing overall operational efficiency (Zhao et al., 2022; Wang et al., 2023).

The steel industry is increasingly focusing on sustainability and environmental stewardship. The steel sector has identified a number of environmental aspects that are part of the steel plants' development strategies. Sustainability is a determinant of steel production (Gajdzik and Burchrt-Korol, 2011; Gajdzik, 2023).Industry 4.0 technologies are being leveraged to optimize energy consumption, reduce emissions, and minimize waste generation (Gajdzik and Sroka, 2021; Flues et al., 2015; Johansson, 2015; Wolniak et al., 2020). Smart energy management systems, advanced process controls, and predictive maintenance contribute to eco-friendly practices and support the industry's commitment to sustainable manufacturing (Horst and Andrade, 2023, Balli and Sel, 2023; Illutiu-Varvara and Aciu, 2022).

2.4. Industry 4.0 technologies and factors

Sustainability is a paradigm in the steel industry (Birat, 2001). In Industry 4.0, sustainability is the strategic purpose of companies in their transformation processes (Bonilla Silvia et al., 2018). The steel technology of the future is DRI (Direct Reduced Iron). Direct Reduced Iron (DRI) is the product of the direct reduction of iron ore in the solid state by carbon monoxide and hydrogen derived from natural gas or coal (https://www.metallics.org/dri.html). Sustainable and smarter processes of steel mills must be linked to the processes of key suppliers (entry into sustainable and smart steel manufacturing) and the processes of key customers (exit from sustainable and smart steel manufacturing). Steel mills are strongly linked to steel product customers. The demands of the steel product consumers, who are themselves, producers, are increasingly high. The processes of the steelworks and the customers of steel products are dependent on each other. Demand data for steel products makes it possible to meet consumer needs. There must be flexibility in the cooperation between producers and consumers. In the steel chain, the flexibility that comes from B2B cooperation can be bimodal, trimodal as well as multi-modal. Steel consumers, working with steel mills, initiate the process of change in steel products to adapt them to markets (Ranjan and Read, 2016). They (steel consumers) are the beneficiaries of steel product innovation, but in the innovation process, the steel mills bear the greatest risk of innovational changes (the time from design to testing to implementation of new production technologies is long, and technological investment in steel mills is very capital intensive) (Rochardson-Barlow et al., 2022; Axelson et al., 2021). In Industry 4.0, smart technologies are being pursued throughout the value chain. Examples of solutions: digital twin (design of new steel products and improving the life cycle of steel products), 3D geometry of the physical components of steel products (steel product design, quality control), computer models for production planning, cloud solutions, and Exchange Information Requirements systems, models to create 4D simulations for better production scheduling, machine control systems, and other technological applications: Resource Planning, Warehouse Management Systems, Transportation Management Systems, Intelligent Transport Systems, Information Security, Customer Relationship Management, Enterprise Content Management. Industry 4.0, with its pillars, strongly influences the planning, production, and logistics processes within and around the steel mills. Collaboration and logistics in the steel chain require cloud computing. Cloud logistics facilitates the introduction of process automation and data analysis to quickly identify trends, consumer behavior, and the actions of competitors. Cloud logistics facilitates the introduction of metallurgical process automation and data analysis. More accurate data on the expectations and habits of steel consumers makes it possible to effectively meet their needs. All individual steps in the steelmaking process are interconnected and integrated with a common supply chain service system (Barreto et al., 2017; Hassanien et al., 2015; Schrauf and Brecher, 2017).

Modern steel product chains cannot function without the IIoT. The Internet of Things is influencing developments by adding sensors to all elements of manufacturing and supply chain processes (Jeschke et al., 2017; Macaulay et al., 2015; Morales et al., 2016). On the way out of the steel mills are innovative warehouses that are fully automated and equipped with robots. Warehouses based on intelligent, self-learning algorithms continuously analyze processes, starting from goods receipt and inventory management to storage and delivery. An intelligent warehouse management system (WMS), can select and prepare a docking slot, optimizing just-in-time and just-in-sequence delivery. Simultaneously, the RFID sensors reveal what has been delivered and send the track-and-trace data to the entire supply chain. The WMS will automatically attribute storage space according to the delivery specifics and request the appropriate equipment to move the goods to the right location autonomously (Khan et al., 2022).

Automation, digitalization, and artificial intelligence connect production machines of all generations and all processes from orders to sales. Technologies analyze material flows and forecast material requirements and harmonize production. Digitalization is also in value marketing, where artificial intelligence is combined with other ICT technologies to better communicate with the customer and personalize products. Digital marketing is the highly integrated information systems and technologies of the two extreme links in the supply chain, i.e. the steel producer and the consumers of steel products (automotive, construction, machinery manufacturers, etc.).

In summary, if an organisation wants to gain a competitive advantage, its value chain must be managed as a system rather than as a set of separate activities (Porter, 1990). Networking approach: horizontal and vertical value chain integration and associated interoperability extend the traditional boundaries of companies to include a network of organisations and stakeholders. New actors are emerging and the role of existing ones is changing. Consequently, new ways of creating and offering value are developing, beyond single value chains (Ibarra et al., 2018). Information technology is changing products, they have become complex systems combining hardware, software, sensors, data storage, microprocessors and connectivity in different ways. Products are smart and connected, they are going through many improvements in the production itself, they include wireless connectivity, thus starting a new era of competition. Products include new features, are more reliable, more useful and better than traditional products. The new nature of products is disrupting traditional value chains and forcing organisations to respond and reorganise processes (Porter and Heppelmann, 2014). Digital transformation is influencing the overall redesign of value chains. Technology builds vision across the value chain and underpins automation to ensure efficiency and competitiveness.

The impact of digital transformation on the value chain not only concerns the specific value chain, but also but also highlights the role of data in the virtual value chain, which is emerging as a new element in the value chain. The premise of the virtual value chain is the generation of data. As part of the digital transformation, data permeates all primary and secondary activities of the value chain, thus influencing every link of value creation. In this way, the virtual value chain derives from and is part of the physical value chain. It is therefore important for companies to analyse the impact of digital transformation on the value chain from a data lifecycle perspective (Qquanquin et al., 2022). Managing data as a valuable business asset in the value chain. Access to data requires its protection, so cyber security management is fundamental to digital processes in chains (Lezzi et al., 2018).

Industry 4.0 technologies such as robotics, automation, and artificial intelligence are transforming the way steel is produced (Hou et al., 2020). These technologies can improve efficiency, reduce downtime, and enhance product quality. For example, robots can be used to perform dangerous or repetitive tasks, while predictive maintenance can help reduce downtime by addressing issues before they become major problems (Shan et al., 2020). The implementation of Industry 4.0 in the steel chain can help to optimize the entire steel supply chain, from raw materials to finished products (Rossini et al., 2020; Lassing et al., 2021). With real-time data, steel manufacturers can make better decisions about production and logistics, ensuring that products are delivered on time and at the right quality (Lassing et al., 2021). Also, technologies such as 3D printing and digital modeling are transforming the way steel products are designed and manufactured (Xie et al., 2020). With these technologies, it is possible to create complex shapes and designs that would have been difficult or impossible to produce with traditional manufacturing methods (Kurdi et al., 2020). Industry 4.0 in the steel chain has the potential to improve efficiency, reduce waste, and enhance product quality (Stojadinovic et al., 2021). By leveraging the power of data and advanced technologies, steel manufacturers can remain competitive in a rapidly changing global market, while also reducing the environmental impact of their operations (Ghobakhloo, 2020).

Similar results indicating the need for smart supply chains were obtained by Virbach (2019). He points out the important role of robotics in the implementation of Industry 4.0 in industry. Robotics and automation have a big potential to be implemented and widespread among the parts of the supply chain. The impact of the implementation of Industry 4.0 on the supply chain was also investigated by Szozda (2017). He also as in our research points out the importance of achieving the continuity of material flow as an important factor of a resilient supply chain. According to his research, the implementation of Industry 4.0 can lead to improvement in the efficiency of internal and external processes. The Chinese examples of using intelligent manufacturing in the steel industry supply chain were described by Zheng et al (2022). According to this research insufficient automation of the supply chain can be a very important problem when an organization implements the Industry 4.0 concept.

According to the literature, many technological factors can be improved when implementing Industry 4.0 in the steel industry supply chain in automation and (Chin et al., 2022). One of the most significant uses of automation and robotics is in the production process. Robotic systems are being used to perform tasks such as welding, cutting, and material handling (Liu et al., 2023). These robots can work continuously without breaks, reducing production time and improving efficiency (Deng, 2022). Robots are also being used to perform dangerous and repetitive tasks, such as handling molten steel, which reduces the risk of injury to human workers (Yao and Wang, 2020) .

Another way that Industry 4.0 is implementing automation and robotics according to literature (Zheng et al., 2022; Govender et al., 2019) in the supply chain of the steel industry is through the use of smart sensors and artificial intelligence (AI). Smart sensors can be used to monitor the performance of equipment and machinery in real time, identifying potential problems before they become critical (Gradim and Teixeira, 2022). AI algorithms can analyze this data to identify patterns and optimize the production process, reducing waste and improving efficiency.

The implementation of Industry 4.0 technologies is transforming the supply chain of the steel industry, and automation and robotics are playing a significant role in this transformation (Ribeiro et al., 2021). Automation and robotics are being used to improve efficiency, productivity, and safety in the production process, logistics, and distribution of steel products (Tantawi et al., 2019). The use of smart sensors and AI is further optimizing the production process, while 3D printing and digital modeling are transforming product design and customization. As the steel industry continues to evolve, the implementation of Industry 4.0 technologies will become increasingly important in driving growth and innovation (Xie et al., 2020; Karabegović et al., 2020).

Also, warehouse automation is an important factor when implementing Industry 4.0 in steel companies (Aravindaraj and Rajan Chinna, 2022). Warehouse automation is the use of technology and machinery to automate warehouse processes, such as inventory management, order fulfillment, and shipping (Moufaddal et al., 2021; kattepur, 2019). With the help of Industry 4.0 technologies, steel companies can automate these processes, resulting in faster and more efficient warehouse operations.

The problems connected with the automation of warehouses in Industry 4.0 conditions in Poland were described by Tubis and Grzybowska (2022). According to the similar technologies as in our research can be implemented for example the digitalization of processes plays one of the key roles in the implementation of Industry 4.0 in the supply chain. It means the widespread usage of technologies like computer systems, mobile technologies, and so on. Similar results were described by Naseem and Young (2021). According to their research, the implementation of Logistic 4.0 in the industry will have a positive impact on the resilience of supply chains to undesirable events occurring.

A very interesting paper about warehouse management in Industry 4.0 was also written by Abbasian et al (2022). In his paper, he points out the importance of workers' preparation (competencies and acceptance of Industry 4.0-related technologies). In our research, we can also observe the importance of the human role in Industry 4.0 implementation in the steel industry.

One of the technologies that can be used in this case is - Automated Storage and Retrieval Systems (ASRS): ASRS is an automated system that stores and retrieves products from a warehouse (Borisoglebskaya et al., 2019). The system consists of a computer-controlled crane that moves along a track and retrieves items from a storage rack. With the help of Industry 4.0 technologies such as sensors, AI, and big data, the ASRS can efficiently manage the inventory of steel products in the warehouse (Youssef et al., 2022).

In the case of warehouse automation, the Internet of Things can be used. With the help of Industry 4.0 technologies such as sensors and big data, IoT can be used to monitor the inventory levels of steel products in the warehouse and automatically reorder them when needed (Lin and Zeng, 2021). As the steel industry continues to evolve, the implementation of Industry 4.0 technologies will become increasingly important in driving growth and innovation, and warehouse automation will play a critical role in this transformation (Spieske and Birkel, 2021).

Mobile technology usage in Industry 4.0 refers to the use of smartphones, tablets, and other mobile devices to support various business operations (Coelho et al., 2021). With the help of Industry 4.0 technologies, steel companies can leverage mobile technology to streamline supply chain operations and make them more efficient. Mobile technology can be used to manage warehouse operations, including inventory tracking and management, order picking, and shipping. With the help of mobile devices, warehouse workers can easily scan barcodes or QR codes to update inventory records in real-time, making it easier to track products throughout the supply chain.

The potential of the usage of mobile technologies in the steel industry supply chain was described by Santos et al (2021). In this paper, the authors describe many mobile technologies that can be used to boast the efficiency of the supply chain in the steel industry. According to the research (Hizam-Hanafiah and Soomro, 2021), mobile technology is one of the most important and most widespread in supply chains when implementing Industry 4.0.

Mobile technology in supply chain management can be used to improve customer service in the steel industry supply chain (Stojadinovic et al., 2021). With the help of mobile devices, customer service representatives can access real-time information about products, orders, and shipping statuses, making it easier to answer customer inquiries and resolve issues quickly (Iakovets et al., 2023).

Also, Big Data is a technology very important for the steel industry supply chain functioning improvement in Industry 4.0 conditions (Mele and Magazzino, 2020). Big data refers to the large volume of structured and unstructured data generated by various sources, including sensors, machines, social media, and other digital platforms. With the help of Industry 4.0 technologies, steel companies can collect, analyze, and interpret big data to gain insights into their operations, products, and customers. In the steel industry, big data analytics can be used to predict equipment failure and prevent downtime. By analyzing data from sensors and machines, steel companies can identify patterns and anomalies that indicate potential issues with equipment (Taticchi et al., 2013). This allows maintenance teams to take proactive measures, such as scheduling repairs or replacements before a breakdown occurs (Fragapane et al., 2022). Big data can be used to optimize the supply chain in the steel industry. By analyzing data from suppliers, manufacturers, and distributors, steel companies can identify inefficiencies and bottlenecks in the supply chain (Lugli et al., 2021). This helps to reduce lead times, improve on-time delivery, and optimize inventory levels. Big data analytics can be used to gain insights into customer behavior and preferences in the steel industry (Aydogan, 2022). By analyzing data from customer feedback, social media, and other sources, steel companies can understand customer needs and preferences, and develop products and services that meet those needs (Jagatheesaperumal et al., 2022, Dossou, 2018). The method can be used to optimize energy consumption in the steel industry (Park and Bae, 2022). By analyzing data from sensors and other sources, steel companies can identify opportunities to reduce energy consumption and costs. This helps to reduce the environmental impact of steel production and increase sustainability (Li, 2023).

In supply chain management in the steel industry, blockchain technology can be used to securely store and share data throughout the supply chain (Son et al., 2021). For example, a steel company can use a blockchain-based platform to track the origin of raw materials, monitor production processes, and ensure compliance with environmental and safety regulations. By providing a secure, immutable record of all transactions, the blockchain can help to improve supply chain efficiency and reduce the risk of fraud and counterfeiting (Ranathunga et al., 2023).

This technology can help to enhance cybersecurity in the steel industry by providing a secure platform for storing and sharing sensitive information. The decentralized nature of the blockchain makes it highly resistant to cyber-attacks, as there is no single point of failure (Otoum et al., 2023). Additionally, by using encryption and other security protocols, blockchain platforms can provide end-to-end security and ensure that data is only accessible to authorized users.

It's worth to prepare a comparison of achieved results with the relevant researches adopting value chain approach. Unlike traditional value chain approaches (Yu et al., 2022; Mohammadi et al., 2022; Lopez et al., 2023) that primarily focus on analyzing activities within a single firm, this paper adopts a broader perspective by considering the entire steel supply chain. It takes into account various stakeholders, including suppliers, manufacturers, distributors, and service providers. By examining the technological factors impacting the entire chain, the study provides a more comprehensive understanding of the interconnectedness and interdependencies among different entities in the steel industry.

While value chain approaches often analyze the flow of physical goods and associated value-added activities, this paper specifically emphasizes the role of technology in the steel supply chain. It goes beyond the traditional value chain analysis (Goyal and Routroy, 2023; Ghosh et al., 2022; Devlin and Yang, 2022) by exploring the impact of Industry 4.0 technologies, such as automation, robotics, and IIoT, on different stages of the steel chain. This technological focus brings a new dimension to the analysis and sheds light on the transformative potential of technology in supply chain management.

The innovative concept in this paper is a categorization of technological factors influencing the steel supply chain into three dimensions: production, distribution, and service. This categorization provides a structured framework for understanding and analyzing the specific technological elements that affect different aspects of the chain. By systematically categorizing these factors, the paper offers a valuable reference point for practitioners and researchers to identify and address technological challenges in specific areas of the steel supply chain.

In contrast to some traditional value chain approaches that may not explicitly consider sustainability aspects (Brankley et al., 2022Khoza et al., 2022), this paper highlights the connection between technology adoption and sustainability objectives. It examines how Industry 4.0 technologies can contribute to resource optimization, waste reduction, and sustainable manufacturing practices in the steel industry. This linkage between technology and sustainability adds a novel dimension to the analysis, demonstrating the potential for technology-driven improvements that align with environmental and social goals.

4.5. Main theoretical implication of the paper

The main theoretical implication of the paper is its contribution to the existing body of knowledge by integrating technology and supply chain management theories, providing insights into the application of Industry 4.0 concepts in the steel industry, identifying dominant technological factors, emphasizing the role of information systems, linking technology to sustainability, and considering cybersecurity in supply chain management. These implications provide a foundation for future research and theoretical development in the field of technology-driven supply chain management.

The study also contributes to the theoretical understanding of Industry 4.0 concepts by exploring their application in the context of the steel industry. It demonstrates how concepts such as automation, robotics, big data, IIoT, and blockchain can be leveraged to enhance the efficiency and performance of the steel supply chain. This extends the theoretical knowledge of Industry 4.0 beyond general manufacturing settings.

Besides the paper contributes to the theoretical understanding of how technology adoption in the steel supply chain can contribute to sustainability objectives. It explores how Industry 4.0 technologies can optimize resource utilization, reduce waste, and support the transition to sustainable manufacturing practices. This theoretical link between technology and sustainability expands the knowledge base on how technological advancements can align with environmental and social goals.

There are some managerial implication which can be formulated on the basis of the paper:

- Managers should prioritize the automation of production processes, including the use of robots and advanced machinery, to improve productivity, reduce downtime, and enhance worker safety. Investments in smart sensors, AI, and predictive maintenance can further enhance process efficiency.
- Managers in steel industry should also leverage mobile technologies to enable real-time communication, data access, and collaboration among supply chain participants. Mobile applications can provide stakeholders with on-demand information, facilitate tracking and tracing of products, and improve overall supply chain visibility.
- It is also worth for organization in steel industry to explore opportunities to collect and analyze large data sets from various sources, including wireless and RFID sensors, to gain insights into machine operations, optimize processes, and improve decision-making. Leveraging cloud services can enable secure and efficient data storage, analysis, and sharing.

Another concepts impotent to implement in steel industry organizations are optimization of processes and sustainability. It worth to enhance efficiency of processes, reduce environmental impact, and support the transition to net-zero carbon emissions. Embracing advanced manufacturing technologies like 3D printing and digital modeling can enable the production of complex and sustainable steel products.

The different areas of technological innovation of the fourth industrial revolution are more and more popular in the steel market (Peters, 2016; Peters, 2017; Gajdzik, 2021). Although the changes have started it will take time to achieve all the necessary conditions of Industry 4.0, and the path to Industry 4.0 consist of large projects (Gajdzik et al., 2021). In Industry 4.0 is making a transition from strategic to operational reality. Bringing breakthroughs in quantum computing, fully autonomous vehicles, and machine-to-machine communication, the so-called fourth industrial revolution has a massive potential to improve existing processes, boost horizontal and vertical collaboration, and develop new steel chains in various industries that are willing to embrace digitalization (Osterried et al., 2020; Chen et al., 2020; Dongdong et al., 2022). Changes in the value chain are determined by the need to continuously build customer value and the necessity to continuously strive for sustainable steel production in the context of resource conservation and the environmental impact of steel plants (Gajdzik et al., 2023; Liu et al., 2022; Piurmehdi et al., 2020). Industry 4.0 technologies are an opportunity for the steel sector to develop a steel sustainable chain (Liu et al., 2023).

3. Materials and methods

The research was conducted in Poland. The obtained database comprised 208 respondents (company executives), including steel mills and steel product manufacturers (e.g. manufacturers of tubes and other long products, manufacturers of steel sheets), steel product distributors including steel product wholesalers and warehouses, distribution centers, steel product consumers including steel structure manufacturers, automotive manufacturing companies and others. The direct surveys were carried out between 2000 and 2022. The extended survey period was conditioned by social constraints due to COVID-19 reasons. The direct surveys were dedicated surveys. The list of companies (business entities) to which the questionnaire was sent (research link) was obtained from the list of members of the Polish Steel Association in Katowice and the Regional Chamber of Commerce (RIG) in Katowice. In the segment of 208 business entities, there were 9 producers of steel and steel products (exhaustive survey, segment=100%), to which they are (were) owners of 2 converter steel mills, 7 electric steel mills, 5 flat product mills, 12 long product mills and 10 tube mills and z/closed sections, 42 other steel product manufacturers, 25 companies that make up the steel product distribution segment (exhaustive survey, the segment accounted for 100%), steel product consumer segments numbered, in total, 132 business entities (companies), including the automotive segment 34 business entities, which accounted for 10% of the total companies in this segment (and their share of the respondents accounted for 25%). A large group of respondents steel and steel products consumers were companies belonging to the finished metal products segment (40% of the steel consumers segment). Other consumers: machinery manufacturers 20 companies and others (a total of 35%).Sampling was purposive, the research used a non-random sampling method to which individuals were selected based on an arbitrary decision by the researcher. The research was conducted by the first author of this paper (an expert in the Polish steel market). The criterion for purposive selection is only that the research participant meets a certain criterion, and this was the first filter question used in the questionnaire, which reads: Does the respondent have knowledge of Industry 4.0 technologies. This question was followed by a question verifying the research participant's knowledge of Industry 4.0 technologies. The research tool was a questionnaire. The CAWI technique was used. In the questionnaire used a five-point Likert scale, where: 1 represented the lowest rating and 5 the highest. The questions were organized according to the degree of increasing technological progress in the market for steel producers and steel product customers, from digitalization and ICTS technology development to the pillars of Industry 4.0. The questions on the pillars of Industry 4.0 used the literature's division into 9 pillars (Erbos, 2019), which became the basis for determining the 5 TSs. Each TS was assigned TFs, or technological factors.

This paper presents one area of research, which was concerned with determining the impact of Industry 4.0 technological factors on steel product chains. The results presented are general because they did not refer to specific steel product chains, but presented respondents' assessments of the impact of Industry 4.0 technology on the development of key segments in the steel chain in Poland. Technologies (the pillars of Industry 4.0) are grouped into five technological segments [TSs] and three respondent segments representing the steel chain in Poland [RSs]: Producer [P], Distributor [D], and Consumer [C] (Figure 1).

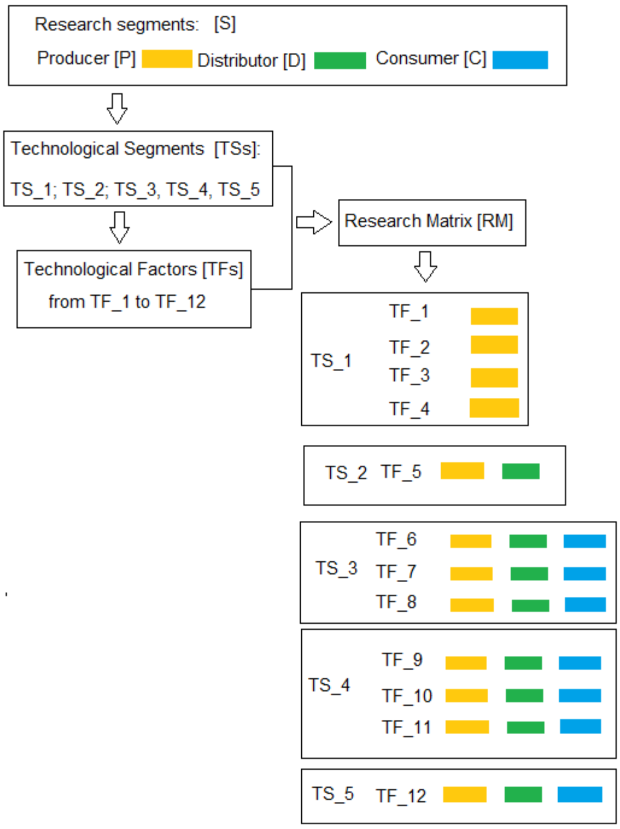


Fig. 1. Research matrix

TS_1 was called [Automation and robotics] and consisted of the following solutions, which are abbreviated in the research as TFs (Technological Factors):

TF_1: Automation of production using single machines (with sensors and sensors deployed).

TF_2: Production automation using collaborative machines with intelligent sensors and additive manufacturing (printing 3D) for own consumption.

TF_3:Automation and robotics of entire production lines (systems) (integration of devices and communication between devices) and technologies of additive manufacturing for the market.

TF_4: Multi-task production lines controlled automatically by systems with machine learning algorithms, and strong robotics of production.

TS_ 2 was called: [Warehouse automation] and consisted of on technological factor:

TF_5: Automation of the storage process (partially or fully automated warehouses) with components of the Warehouse Management System (WMS).

TS_3 was called: [Computer systems, systems integration, mobile technologies] and consisted of:

TF_6: Mobile communication and connectivity technologies.

TF_7: Development and compatibility of computer systems in the supply chain (SCM)

TF_8: Network and chain integration of enterprises' computer systems (end-to-end supply chain).

TS _4 was called : [Big Data and IIoT] and included:

TF_9: Devices and technologies (wireless sensors, RFID sensors) generating data on the operation of machines and technological installations in real-time.

TF_10: Extended databases (Big Data), process visualization, augmented reality, simulation computing.

TF_11: Access to cloud services and the Industrial Internet of Things (IIoT).

TS_5 was called: [Blockchain and cybersecurity] was assessed (TF_12). In the segment, no sub-segmentation was used, due to the strong links between blockchain operations (structure) and data protection and security of data transmission in steel chains.

Such fields (Questions in the survey: Qs) of the influence of technological factors on the steel supply chain are used in the research:

Q1: The first question was about the impact of process improvement by automation and robotics (TF_1, TF_2, TF_3, TF_4) on the development of the steel supply chain.

Q2: The second question was about the impact of the automation (TF_5) of the storage process on the development of the steel supply chain.

Q3: The third question was about the impact of ICT (TF_6, TF_7, TF_8) on the development of the steel supply chain.

Q4: The fourth question was about the impact of Big Data and IIoT (TF_9, TF_10, TF_11) on the development of the steel supply chain.

Q5: The fifth question was about the impact of the improvement connected with steel blockchain and cybersecurity (TF_12) on the development of the steel supply chain.

Particular questions (Qs) were addressed to proper research segments (RSs).

The study of the impact of technology on the development of the supply chain, seems obvious, but the author of the study was concerned with determining the degree of change through a worn Likert scale from 1 to 5. Gradualism is the basis for establishing the framework of the steel supply chain maturity model for industrial transformation according to the idea of Industry 4.0. Citing scientific publications (Peters, 2017; Castelo-Branco et al, 2019; Gajdzik and Wolniak, 2021), a preliminary assumption is made that the transition of companies from the level of the third revolution to the level of the technology of the fourth industrial revolution, or, according to the nomenclature of successive industrial revolutions, from level 3.0 to level 4.0, is underway in the sector under study.

4. Results

The surveyed segments of the steel chain , in presentation: Table from 1 to 5, are color-coded: orange: producer (P), green: distributor (D), blue: consumer (C). red color denotes the responses of respondents (share of responses in segments of the scale from 1 to 5), while for the sake of 100% (rows of the table), a column NoR. or non-response was introduced, which includes respondents who did not answer a specific question, refraining from choosing the impact of a particular technology (Technological Factor) on the transformation taking place. The last column of the table contains a graph of the distribution of responses: from NoR, through a Likert scale from 1 to 5.

Answers to research questions:

(Q1): Questions about the influence of technological factors (TF_1, TF_2, TF_3, TF_4) on the steel chain were addressed to the steel mills and steel product producers, who were abbreviated [P] in the research. The results of the research are presented in Table 1.

The table shows that more than ¾ of the respondents of the [P] segment indicated high and very high ratings (4 or 5). Each level of automation, from individual machines and production cells to robots, is important for building a smart steel chain in Poland. Dominants for technological factors TF were: TF_1: dominant 5, TF_2: dominant 4, TF_3: dominant 5, TF_4: dominant 4. According to the respondents, automation of steel production processes is an important step towards creating smart steel chains.

The automation of processes is related to the specifics of production, where the most relevant factors are those that have a key impact on the continuity of material flow throughout the logistic supply chain. Production management should focus on ways to improve the efficiency of processes, both internal and external to the supply chain, as well as their continuous monitoring and evaluation. For this reason, production automation is linked to the robotics of production machinery, but also to the logistical handling of the entire production process, primarily in the area of warehousing and internal transport (Business Process Automation). Therefore, the next segment [TS_2] of the study concerned steel product warehouses. TS_2

[Warehouse automation] consisted of one factor: TF_5: Automation of the storage process (partially or fully automated warehouses) with components of the Warehouse Management System (WMS).

(Q2): the question (Q2) on the impact of the automation of the storage process on the development of the supply chain was addressed to two segments: steel producers [P], who have their own sales warehouses, and companies involved in the distribution of steel products, these respondents were marked with the letter [D]. The results of the assessment are presented in Table 2.

The percentages in Table 2 confirm the existence of warehouse automation in improving supply chains (¾ of respondents indicated good and very good ratings, both in the segment of manufacturers who had their steel product warehouses and in the segment of retailers (distribution market). Data in Table II show that the dominants for each answer were 4. Warehouse process automation and WMS solutions are used to coordinate warehouse operations. These are highly specialized systems that streamline all the processes that take place in warehouses.

Free retrieval of information at any point in the chain is contingent on the degree to which appropriate IT tools and technologies are implemented in all links of the chain: uniform standard for identifying goods, services,locations(EANCOM), automatic identification, electronic communication including electronic data interchange(EDI), integrated information systems of the SCM class.

(Q3): based on this assumption, further technological factors were assessed and categorized into the TS_ 3 called: [Computer systems, systems integration, mobile technologies]. With such factors: TF_6: Mobile communication and connectivity technologies.

TF_7: Development and compatibility of computer systems in the supply chain (SCM)

TF_8: Networking and chain integration of enterprises' computer systems (end-to-end supply chain). The technological factors (TF_6, TF_7, TF_8) were addressed to all participants of the research, i.e. steel Producers [P], Distributors of steel products [D], and Consumers of steel products [C]. The results are presented in Table 3.

Table 1. Automation and robotics of processes as technological factors [TF] in the segment: steel producers [P] in Poland (assessment of the impact of the factors on the steel chain)

TF	S: Producer	No Response	Likert scale:					Research Figures
		noR	1	2	3	4	5	
TF_1	P	3.23%	0.00%	0.00%	17.74%	30.65%	48.39%	
TF_2	P	3.23%	0.00%	3.23%	12.90%	46.77%	33.87%	
TF_3	P	8.06%	0.00%	0.00%	11.29%	38.71%	41.94%	
TF_4	P	3.23%	0.00%	1.61%	16.13%	43.55%	35.48%	

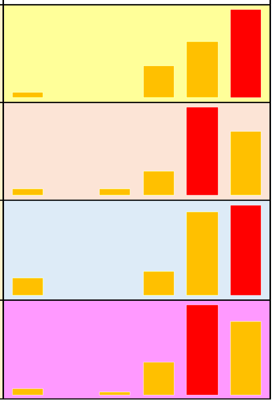


Table 2. Warehouse automation as a technological factor [TF] in the segments: steel producers [P] and steel product distributors [D] in Poland (assessment of the impact of the factor on the steel chain)

TF	S: Producer and Distributor	No Response	Likert scale:					Research Figures
		noR	1	2	3	4	5	
TF_5	P	3.23%	0.00%	1.61%	17.74%	45.16%	32.26%	
TF_5	D	4.41%	0.00%	5.88%	16.18%	42.65%	30.88%	

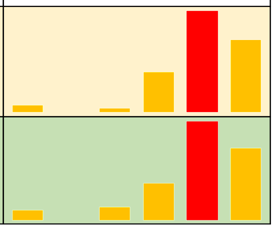
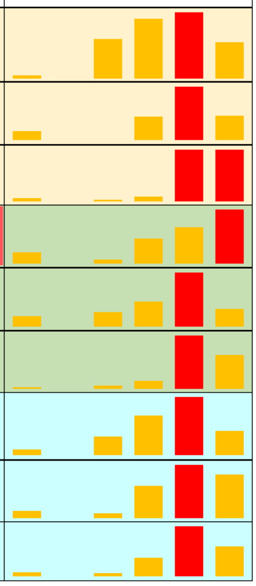


Table 3. Computer systems and mobile technologies as technological factors [TF] in the segments: steel producers [P], steel product distributors [D] and steel product consumers [C] in Poland (assessment of the impact of the factors on the steel chain)

TF	S: Producer, Distributor, Consumer	No Response	Likert scale:					Research Figures
		noR	1	2	3	4	5	
TF_6	P	1.61%	0.00%	19.35%	29.03%	32.26%	17.74%	
TF_7	P	8.06%	0.00%	0.00%	20.97%	48.39%	22.58%	
TF_8	P	2.94%	0.00%	1.47%	4.41%	45.59%	45.59%	
TF_6	D	8.82%	0.00%	2.94%	19.12%	27.94%	41.18%	
TF_7	D	8.82%	0.00%	11.76%	20.59%	44.12%	14.71%	
TF_8	D	1.61%	0.00%	3.23%	8.06%	53.23%	33.87%	
TF_6	C	3.85%	0.00%	12.82%	26.92%	39.74%	16.67%	
TF_7	C	5.13%	0.00%	3.85%	23.08%	37.18%	30.77%	
TF_8	C	3.85%	0.00%	2.56%	17.95%	47.44%	28.21%	



Based on the data in Table 3, it was found that ratings of the impact of computer systems and mobile technologies on the creation of smart chains for steel products were very high (dominants 4 or 5). For all chain participants, technological factor 8, i.e. network and chain integration (end-to-end supply chain), was of the highest importance; the distribution of responses was as follows: [P]: the share of ratings 4 and 5 accounted for 91.18%, [D] the share of ratings 4 and 5 accounted for 87.10%, [C] the share of ratings 4 and 5 accounted for 75.64%. 70% of supply chain participants considered it important to create, as far as possible, a single integrated IT system, which, regardless of the information processing, would allow chain participants to have free access to a consistent and at the same time convenient data exchange model (integrated SCM IT systems)-TF_7. The widest range of answers was obtained in the assessments of the impact of mobile technologies on building a smart steel chain (TF_6), with 50% [P] and just over 50% of respondents in segments [D] and [C] selecting ratings of 4 or 5. Mobile technologies were rated highest in the steel distribution segment. **(Q4):** supply chain improvement cannot be realized without Big Data and IIoT. The segment TS_4 included: TF_9: Devices and technologies (wireless sensors, RFID sensors) generating data on the operation of machines and technological installations in real-time, TF_10: Extended databases (Big Data), process visualization, augmented reality, simulation computing, TF_11: Access to cloud services and the Industrial Internet of Things (IIoT). The evaluation question addressed three groups of respondents: [P], [D], [C]. The results are shown in Table 4.

Table 4. Big Data and IIoT as technological factors [TF] in the segments: steel producers [P], steel product distributors [D] and steel product consumers [C] in Poland (assessment of the impact of the factors on the steel chain)

TF	S: Producer, Distributor, Consumer	No Response	Likert scale:					Research Figures
		noR	1	2	3	4	5	
TF_9	P	8.06%	0.00%	3.23%	14.52%	50.00%	24.19%	
TF_10	P	4.84%	0.00%	6.45%	24.19%	48.39%	16.13%	
TF_11	P	1.61%	0.00%	20.97%	27.42%	33.87%	16.13%	
TF_9	D	2.94%	0.00%	2.94%	13.24%	41.18%	39.71%	
TF_10	D	1.47%	0.00%	8.82%	7.35%	33.82%	48.53%	
TF_11	D	8.82%	0.00%	8.82%	17.65%	41.18%	23.53%	
TF_9	C	3.85%	0.00%	2.56%	8.97%	25.64%	58.97%	
TF_10	C	1.28%	0.00%	10.26%	10.26%	23.08%	55.13%	
TF_11	C	3.85%	0.00%	15.38%	21.79%	42.31%	16.67%	

Table 5. Blockchain and cybersecurity as technological factors [TF] in the segments: steel producers [P], steel product distributors [D] and steel product consumers [C] in Poland (assessment of the impact of the factors on the steel chain))

TF	S: Producer, Distributor, Consumer	No Response	Likert scale:					Research Figures
		noR	1	2	3	4	5	
TF_12	P	14.52%	0.00%	4.84%	14.52%	32.26%	33.87%	
TF_12	D	5.88%	0.00%	0.00%	7.35%	42.65%	44.12%	
TF_12	C	2.56%	0.00%	1.28%	8.97%	46.15%	41.03%	

Based on the responses (%) in Table 5, it was found that in the segments: [P] and [C], the technology factor TF_9 received the highest ratings ([P]: 74.19% of indications for ratings 4 and 5; [C]: 84.64% of the total indications for ratings 4 and 5. For [D], the TF_10 factor was important (82.35% of indications), but right behind it was the TF_9 factor with 80.88% of indications for 4 and 5. The least trust (at the current stage of development of smart chains) was placed by respondents on TF_11. In their opinion, the use of cloud and IIoT still needs time. The dominants for the evaluated technological factors were 4 or 5.

(Q5): the last segment TS_5 [Blockchain and cybersecurity] was addressed to all supply chain segments. The results of the study are summarised in Table V. The impact of security (cybersecurity) and blockchain solutions on securing steel supply chains was assessed (TF_12).

Based on the sum of the indications for ratings 4 and 5, it was found that the segments [D] and [C] each had 87% ([D]:86.76%, [C]; 87.18%) of indications for high and very high ratings. The [P] segment had only 66.13% of indications for grades 4 and 5. The dominants in the [P] and [D] segments were 5 and in the [C] segment were 4.

4.1. Research findings

Based on the results, the study argues that Industry 4.0 represents an 'evolution' in steel chain processes and a potential 'revolution' in the value proposition of steel chains, and concludes that the majority of steel producers, distributors, and consumers see opportunities for Industry 4.0 technology in improving steel chains. The study looks at Industry 4.0 from a managerial perspective. No strong differences were observed in assessments of the impact of technological factors on steel chains. Managers perceive Industry 4.0 as a bundle of enabling technologies for steel supply chains. Based on the analysis of respondents' answers, it was established that Industry 4.0 technologies are of great importance for the development of steel and steel products supply chains. The progressive automation of processes and computer handling of technologies, advanced manufacturing technologies, process visualization, and computer simulations are, according to respondents, significantly influencing the creation of smart steel chains. At the current stage of chain improvement, the activities directed at integrating the information systems of the steel chain participants received the highest marks. Information systems are covering more and more functions responsible for sourcing, production planning, storage, transport, demand forecasting, and customer service. In the steel sector, RFID technologies that identify steel product components and streamline flows are useful (Panigrahi et al., 2021). The intelligent steel chain also includes fully automated warehouses for steel products, such warehouses are already present in the Polish steel market and more will follow in the future. However, smart chains need huge data sets about participants' processes (e.g. process maps and paths, tracking of equipment operation, and real-time process monitoring), which in turn need cloud computing and IIoT. These technologies, although highly rated as enablers of smart chains in the opinion of the respondents, are still being tested (trust in your technology is being built slowly). The same is true for blockchain in the steel sector and cybersecurity (data standards, information blocks, security certificates, etc. are being developed gradually). According to the Steel Alliance Against Counterfeiting (SAAC), more than 53% of the steel industry has come across fake products during their day-to-day operations, leaving manufacturers to deal with high costs of forgery and plagiarism. Blockchain can be leveraged to create and assign a unique digital identity to a physical product and trace its path through the entire supply chain. All steps of upstream production, including trading and processing, are registered, logged, and traced with a certificate. Contrary to the physical ones, these digital certificates can be found, analyzed, and retrieved instantly. Documentation can be attached to the product and easily shared between relevant parties, providing more trust (Grừll, 2022). In transformation to net zero (CO2), the blockchain allows metal manufacturers to replace mandatory hard copy documents with digital records and to assess CO2 emissions, immutably stored on a decentralized platform that serves as the industry’s single source of truth.

5. Discussion

The implementation of Industry 4.0 in the steel sector leads to the implementation of big amount of technologies and new solutions to the steel production processes (Shi et al., 2020). When we implement the Industry 4.0 concept in the entire steel chain it has a significant impact on the entire steel chain, from raw materials to finished products. Industry 4.0 can help steel manufacturers to optimize their use of raw materials, reducing waste and improving efficiency (Xiao and Zeng, 2021). Smart sensors and IoT devices can be used to monitor the quality and composition of raw materials, allowing manufacturers to make adjustments to their processes to ensure consistent quality (Sawangwong and Chaopaisarin, 2023).

Industry 4.0 emphasizes the integration of smart technologies for automation and improved operational efficiency (Dabvis et al., 2012; Fragapane, et al., 2015; Shi et al., 2020). The study's findings, where more than 75% of steel producers highly value automation and robotics, align with the theory. This suggests a recognition of the importance of automated processes in building smart steel chains.

Also some researches (Khan et al., 2022; Moufaddal et al., 2021) about Industry 4.0 indicate the use of advanced technologies like RFID and WMS for optimized warehouse operations. In presented research Positive ratings (approximately 75%) for warehouse automation reflect the alignment with Industry 4.0 principles. The emphasis on WMS indicates a practical application of digital technologies in improving supply chain processes.

In others international papers (Park and Bac, 202; Zhao et al., 2022) it can be observed importance of Big Data and IIoT in manufacturing and espetially steel industry (Niekurzak and Kubińska-Jabcoń, 2021). The study's results, with high ratings ranging from 74.19% to 84.64% for factors related to big data and IIoT, suggest a strong theoretical underpinning in the adoption of data-driven technologies. The focus on TF_9 (Devices and technologies generating data) and TF_11 (Access to cloud services and IIoT) aligns with Industry 4.0 principles, emphasizing the importance of real-time data in decision-making.

Otoum et al. (2023) emphasizes blockchain for transparency, traceability, and cybersecurity for protecting sensitive data. The study's findings, with approximately 87% positive perceptions of blockchain and cybersecurity, align with the theoretical foundations of Industry 4.0. The application of blockchain to trace the entire supply chain and enhance trust reflects a commitment to transparency and security, key principles of Industry 4.0.

The study reveals a strong emphasis on integrating information systems across the steel supply chain. This aligns with the Industry 4.0 principle of creating a seamless, end-to-end digital ecosystem (Culot, 2022). The positive ratings for big data and IIoT technologies indicate a shift towards data-driven decision-making, a key aspect of Industry 4.0.

The research presented in the paper has some limitations worth to mention. The research is limited to the steel producers, distributors, and consumers in Poland. The findings may be only partially applicable to other countries or regions with different industrial contexts or technological landscapes. he research relies on self-reported data obtained through surveys. Self-reported data may be subject to response bias, where respondents may provide socially desirable answers or inaccurately report their perceptions and behaviors. During the research we tried to avoid those biases. The paper focuses on specific technological factors related to automation, robotics, computer systems, mobile technologies, big data, IIoT, blockchain, and cybersecurity. Other relevant technological factors or emerging technologies that could impact the steel chain may not be considered.

On the basis of research presented in this paper it can be pointed out what can be future direction of the research about the described topic. Future research can delve deeper into the specific areas of automation and identify opportunities for further improvements, such as advanced robotics, process optimization, and integration of automation technologies. The research emphasizes the importance of warehouse automation in improving supply chains. Future studies can focus on exploring innovative technologies and approaches for automating the storage process in steel product warehouses, such as fully automated systems, Warehouse Management Systems (WMS), and intelligent inventory management. Also potential further research can explore the integration of computer systems across the entire supply chain, including steel producers, distributors, and consumers. Additionally, the impact of mobile technologies on various aspects of the steel chain can be further investigated to identify potential areas for improvement and optimization.

6. Conclusion

New technologies in steel chains are an opportunity for steel market development. Industry 4.0 technologies are increasingly entering steel product chains. Mobility, immediacy, immediacy, ubiquity, flexibility, compatibility, accessibility, personalization, communication (information exchange), geolocalisation, etc., are all characteristics that describe the technological factors under study. The individual technologies of Industry 4.0, which in the research were included in five segments of factors influencing the development of steel market chains in Poland, were, by the vast majority of respondents, rated high (rating 4) and very high (rating 5). It still takes time for chain participants to convince themselves (become more confident) about computer cloud, IIoT, or blockchain solutions (the latter require the support of politicians as part of the development of the European steel industry). At this stage of change, supply chain actors are seeking to integrate key business processes between cooperating companies in the chain, leading to increased collaboration between companies and a multiplication of benefits.

The research conducted in the Polish steel industry among 208 respondents has illuminated the significant influence of Industry 4.0 technologies on the steel supply chain. The study, organized into five technological segments, reveals compelling insights. Firstly, in the realm of Automation and Robotics (TS_1), more than three-quarters of steel producers (Segment [P]) recognize the pivotal role of automation, spanning from individual machines to entire production lines, in the establishment of intelligent steel chains.

Moving to Warehouse Automation (TS_2), a majority of respondents, including steel producers and distributors (Segments [P] and [D]), express unanimous support for the positive impact of warehouse automation. The emphasis on Warehouse Management Systems (WMS) is notably acknowledged.

In the domain of Computer Systems and Mobile Technologies (TS_3), the study underscores the critical importance of network and chain integration for creating smart steel chains. This sentiment resonates across all segments, including Producers [P], Distributors [D], and Consumers [C], with over 75% of respondents assigning high ratings to these technological factors.

Big Data and IIoT (TS_4) emerge as significant contributors to the steel supply chain, with wireless sensors and extended databases (Big Data) garnering strong support, particularly in the realm of real-time data generation. However, the adoption of cloud services and Industrial Internet of Things (IIoT) is perceived as requiring further development. Lastly, in the realm of Blockchain and Cybersecurity (TS_5), distributors and consumers (Segments [D] and [C]) overwhelmingly acknowledge the impact of these technologies on securing steel supply chains. In contrast, producers (Segment [P]) exhibit a slightly lower acknowledgment rate, indicating varied perceptions across segments.

The findings suggest that Industry 4.0 signifies an evolutionary step in steel chain processes and a potential revolution in the value proposition of steel chains. Managers across segments perceive Industry 4.0 as a suite of enabling technologies for steel supply chains, underscoring the importance of automation, digitalization, and integration in the pursuit of creating smart and efficient steel chains. While certain technologies, such as computer systems and mobile technologies, enjoy widespread acceptance, others, like blockchain and IIoT, are in the process of gaining trust and achieving broader implementation in the steel industry. The study concludes with a collective recognition of the opportunities presented by Industry 4.0, highlighting the need for ongoing technological advancements to enhance the efficiency and resilience of the steel supply chain.

The main scientific value of the presented paper lies in its meticulous examination of Industry 4.0 technologies in the steel supply chain, providing a valuable reference for researchers, practitioners, and policymakers interested in understanding the dynamics of technological transformation within the steel industry, with potential implications for broader manufacturing contexts.

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