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Thematic Section - Digital Transformation of Supply Chain Management

Application of the RAMI4.0 framework in Purchasing and Supply Management: a case study of a Brazilian Steel Company

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Abstract

Paper aims: This study characterizes Purchasing and Supply Management (PSM) projects in the context of Industry 4.0 (I4.0) at a Brazilian steel company, using the reference architecture model industry 4.0 (RAMI4.0) as a basis.

Originality: The article adapts RAMI4.0 to the PSM context and empirically evaluates the model, promoting digitalization practices in PSM.

Research method: An in-depth case study was conducted using participant observation, document analysis, individual interviews, and focus groups with PSM professionals.

Main findings: By adapting the life cycle (dimension) to the stages of PSM deployment, this study establishes a framework for monitoring and optimizing activities throughout the PSM process, offering valuable insights.

Implications for theory and practice: The customization and evaluation of the RAMI4.0 model for PSM can serve as a reference framework for companies seeking to drive the digital transformation of the PSM function. This model offers a strategic perspective on how to integrate Industry 4.0 technologies across various organizational levels, with the goal of promoting digital PSM.

Keywords

Purchasing and Supply Management (PSM). Industry 4.0 (I4.0). RAMI4.0.

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Conflict of Interest
The authors declare that they have no financial conflicts of interest that could have influenced the work reported in this article.

Ethical Statement
The authors declare that this research did not require ethical approval as it did not involve any experiments on humans or animals.

1. Introduction

According to the Chartered Institute of Procurement & Supply (2020), Purchasing and Supply Management (PSM) is a strategic business function responsible for identifying, accessing, and managing sources of supply in alignment with organizational needs and objectives. PSM requires a comprehensive understanding of supplier markets, as well as technical and commercial dimensions (Cousins et al., 2006), which collectively support the effective execution of business strategies (Monczka et al., 2015). Beyond its operational role, PSM adds significant value to the organization by shaping the design and strategic configuration of supply networks, thereby enhancing organizational responsiveness (Patrucco & Kähkönen, 2021), particularly in dynamic and rapidly changing environments (Wynstra et al., 2019).

Recent research highlights the significant role of Industry 4.0 (I4.0) technologies in enhancing the performance of PSM functions (Fernandes et al., 2021, 2023; Sá et al., 2022; Garay-Rondero et al., 2020; Legenvre et al., 2020; Nasiri et al., 2020; Bals et al., 2019; Frank et al., 2019). I4.0 facilitates the integration of business and manufacturing processes, fostering greater collaboration among stakeholders across the value chain, particularly suppliers and customers (Shaharudin et al., 2023; Ivanov et al., 2022). The digitalization enabled by I4.0 introduces process optimization and increases overall supply chain efficiency. Access to real-time information enhances process visibility, supporting faster and more informed decision-making. Furthermore, automation and digital technologies contribute to productivity gains and error reduction. Ultimately, I4.0 transforms conventional operations into smart, interconnected supply chains, thereby improving efficiency and reducing operational costs (Caiado et al., 2022; Li, 2020).

To support the adoption of Industry 4.0 (I4.0) technologies, various studies have proposed standardized industrial architectures aimed at guiding equipment implementation and network management (Zheng et al., 2018; Adolphs et al., 2015; Hermann et al., 2016). In addition, several conceptual frameworks have been developed to facilitate the structured adoption of smart technologies within the I4.0 context (Frank et al., 2019; Zheng et al., 2018). Among these reference models, the Reference Architectural Model Industrie 4.0 (RAMI4.0) is particularly noteworthy due to its broad applicability and its comprehensive framework for analyzing technological capabilities and integration pathways (Adolphs et al., 2015).

Despite notable advancements, the implementation of Industry 4.0 (I4.0) concepts continues to present significant challenges (Caiado et al., 2022). The majority of existing studies emphasize the applicability of the Reference Architectural Model Industrie 4.0 (RAMI4.0) within manufacturing environments (Lindner et al., 2023; López et al., 2023; Grefen et al., 2022; Çınar et al., 2021; Murugaiyan & Ramasamy, 2021), while research extending its use to the PSM domain remains both recent and limited. Nakagawa et al. (2021) argue that current architectural frameworks are insufficient to fully support I4.0 processes, as their high level of abstraction and lack of detailed documentation often hinder effective project management and implementation. Therefore, there is a critical need for more empirical studies focused on the adoption of I4.0 technologies in PSM, aimed at identifying practical challenges and informing necessary adaptations of existing architectures. Furthermore, to the best of our knowledge, no studies have explicitly examined the relationship between architectural frameworks and the adoption of I4.0 technologies within the steel industry sector of considerable global economic importance.

In order to address this research gap, particularly regarding the empirical applicability of the RAMI4.0 model within the PSM function, this study aimed to answer the following research question: How can the PSM function of a steel company be digitally transformed based on the characterization of Industry 4.0 projects through the lens of the three dimensions of the RAMI4.0 model? Accordingly, the general objective of this research was to characterize PSM projects developed in the context of Industry 4.0 (I4.0) at a Brazilian steel company, using the RAMI4.0 reference architecture as the analytical framework. The specific objectives were: (1) to identify the I4.0-related PSM projects implemented within the company under study; (2) to characterize each project in terms of its objectives, the technologies employed, and the type of material involved; and (3) to analyze each project with respect to the three dimensions of RAMI4.0, namely, the life cycle, architectural layers, and hierarchy levels.

The proposed analytical model incorporates the three dimensions of the RAMI4.0 framework: the life cycle (specifically focusing on the Purchasing and Warehouse phases), the architectural layers (physical world, integration, information/communication, and business), and the hierarchy levels (Product, Field/Control Devices, Workstation, Company, and Connected World). Strategic PSM projects implemented at the steel plant were analyzed and characterized according to this multi-dimensional framework, enabling a structured interpretation of how Industry 4.0 technologies are integrated into supply-related processes.

This study offers a significant contribution to the literature by addressing an existing research gap through the adaptation of the RAMI4.0 model, traditionally applied within smart manufacturing contexts—to the adoption of Industry 4.0 technologies in the smart supply chain domain. In doing so, it extends the prevailing understanding of RAMI4.0 beyond its conventional application in manufacturing systems by demonstrating its relevance and applicability within the PSM function. Furthermore, it enriches the existing body of knowledge regarding the use of RAMI4.0 in the steel industry, particularly in relation to supply chain operations. From a managerial perspective, the proposed customization of the RAMI4.0 framework for smart supply chains provides firms with a more integrated approach to manufacturing and supply management, promoting more efficient coordination of materials, information, and logistics. This integrated approach enhances supply chain agility, supports data-driven decision-making, and strengthens resilience in increasingly digital and automated industrial environments.

The proposed architecture was empirically evaluated through an analysis of Procurement and Supply Management (PSM) projects implemented within a Brazilian steel company, using the RAMI4.0 framework as the analytical lens. This evaluation illustrates how Industry 4.0 technologies align with and support the foundational principles of smart supply chains, with a particular focus on two key product categories: raw materials and spare parts. By grounding the analysis in real-world projects, this study offers a novel perspective and generates practical insights for organizations aiming to implement I4.0 technologies in their PSM functions. The findings underscore the model's practical relevance and applicability, demonstrating its potential to guide digital transformation efforts within supply-related processes across industrial contexts.

Following this introductory section, the remainder of the article is structured as follows. Section 2 provides a comprehensive review of the literature on PSM performance and strategic roles, along with an overview of Industry 4.0 reference architectures, with particular emphasis on the RAMI4.0 model. Section 3 describes the methodological approach, outlining the research design, stages, and the application of the RAMI4.0 framework. Section 4 presents the empirical results derived from the case analysis. Section 5 offers a discussion of the findings considering the existing literature. Finally, Section 6 presents the study's conclusions and highlights potential directions for future research.

2. Literature Review

2.1. Purchasing and Supply Management

Purchasing and Supply Management (PSM) represents a strategic evolution from traditional purchasing practices, shifting the focus from operational transactions to a broader, value-driven approach (Chartered Institute of Procurement & Supply, 2020). As a critical organizational function, PSM is responsible for sourcing raw materials, inputs, and semi-finished products from a global supplier base to support the production of goods and services destined for end customers (Pereira et al., 2020).

To enhance the strategic relevance of PSM, organizations must cultivate advanced market intelligence and in-depth knowledge of supply chain dynamics (van Weele & van Raaij, 2014). Strategic investments in PSM contribute to greater organizational resilience and responsiveness, positioning the function as a key enabler of business strategies aimed at improving competitiveness and ensuring long-term sustainability, particularly in rapidly evolving and uncertain environments (Steiber & Alänge, 2016).

The strategic importance of PSM extends beyond internal organizational operations, as external suppliers account for approximately 60% to 80% of total organizational costs (Monczka et al., 2015; van Weele & van Raaij, 2014. This financial significance underscores the evolving role of PSM professionals, who are increasingly expected to develop strategic competencies and contribute to broader organizational objectives (Wynstra et al., 2019). The PSM function should thus be recognized not merely as a cost-reduction mechanism, but as a creator of strategic value (Schütz et al., 2020; Schiele, 2007; Cousins et al., 2006). Achieving this expanded role requires targeted training and development for front-line PSM professionals to equip them with the skills necessary to drive innovation, collaboration, and long-term value creation (Carnovale & DuHadway, 2021; Stek & Schiele, 2021).

The literature frequently highlights six strategic objectives of PSM that contribute to enhancing organizational performance and resilience. These include: (1) fostering innovation in supply sources to mitigate contractual and operational risks, thereby ensuring supply continuity and long-term sustainability (Luzzini et al., 2015; van Weele & van Raaij, 2014; Schiele, 2010; (2) guaranteeing the availability of critical stock items and production parts to prevent disruptions in operations (Topan et al., 2020); (3) optimizing storage processes to improve operational efficiency, maximize capacity utilization, and ensure inventory accuracy (Wang et al., 2010); (4) enhancing productivity and accuracy in invoice processing while simultaneously reducing administrative costs (Frohlich & Westbrook, 2001); (5) replacing manual controls with automated systems to increase process efficiency and quality (Crespi et al., 2007); and (6) improving the productivity and effectiveness of distributing spare parts and raw materials across the supply network (Topan et al., 2020).

Within operational activities, PSM encompasses two main process groups: material acquisition and warehouse management. Key acquisition activities include quotation, negotiation, contracting, and order monitoring, which relate to suppliers, transportation, and quality control (Monczka et al., 2015), involving planning, evaluation, and control of strategic supply decisions (Pereira et al., 2020). Warehouse management involves receiving, checking, loading, unloading, storing, invoicing, and dispatching materials (van Weele, 2009). Strategies for warehouse operations include physical space design, material location determination (Zhang et al., 2000), and decisions on outsourcing activities (Lee, 2006), as well as material flow patterns, such as first in, first out (FIFO) versus last in, first out (LIFO) (Wang et al., 2010).

2.1.1. An overview of PSM in the steel industry

The steel industry plays a vital role in global economic growth, significantly impacting manufacturing, gross domestic product, and job creation. Projections by the Instituto Aço Brasil (2023) had estimated that crude steel production in Brazil would reach 32.4 million tons in 2023, positioning the country as the ninth-largest producer globally, accounting for 1.7% of total world production, which was expected to reach 2 billion tons (Instituto Aço Brasil, 2023).

Given its economic significance, the organizational transformation driven by I4.0 is essential, especially since the steel industry supplies inputs to various sectors and is influenced by their demands (Gajdzik & Wolniak, 2021).

In PSM, materials managed in the steel industry include energy, raw materials, and maintenance, repair, and operation (MRO) materials (Fernandes et al., 2021). Raw materials like iron ore and coke represent the majority of steel manufacturing costs (Xiong & Helo, 2008), while auxiliary materials encompass casting, machining, and processing inputs, as well as services like transportation (Ocheri et al., 2017).

Spare parts management plays a critical role in ensuring operational continuity within the steel industry. Effective supply chain strategies in this context aim to balance cost efficiency with high levels of customer satisfaction (Caldas et al., 2019). However, managing spare parts poses significant challenges, as meeting customer service expectations often requires maintaining elevated inventory levels (Khajavi et al., 2014). Achieving optimal service levels at competitive costs necessitates minimizing maintenance-related downtime, which depends on the timely availability of high-quality replacement components (Frazzon et al., 2019). This task is further complicated by factors such as the vast number of distinct parts, the substantial financial impact of customer downtime, and the risk of inventory obsolescence (Frazzon et al., 2019).

Addressing the complexities inherent in spare parts management requires a comprehensive analysis of how strategic projects align within the broader supply chain, as well as the identification of appropriate technologies and tools to support PSM processes. Gajdzik & Wolniak (2021) highlight that the steel industry is increasingly advancing toward Industry 4.0 through the implementation of high levels of automation in its production processes. This digital transformation presents new opportunities to enhance the efficiency, responsiveness, and integration of spare parts management within smart supply chains.

I4.0 can help overcome several challenges faced by the industrial sector. Researchers have highlighted the main barriers to digital transformation. Shabur et al. (2023), in their analysis of the steel production sector, identified the key obstacles to the implementation of I4.0 in the current context, with 'high capital investment' being the most significant. Similarly, Mishra et al. (2023) pointed out the lack of adequate support infrastructure, the absence of real-time control systems, and the extended learning time due to insufficient knowledge transfer as major obstacles to the adoption of these technologies in this context. Once the challenges and barriers are identified, the path to adapting to these new practices and trends becomes clearer and more reasonable.

2.2. Industry 4.0 Reference Architecture

I4.0 employs various reference architectures, each differing in content, format, and purpose, with distinct architectural requirements based on specific implementation contexts (Nakagawa et al., 2021). A reference architecture serves as a model that delineates descriptions and actions under a system's rules or constraints (Sage & Rouse, 2014).

Notable reference architectures include:

1. Industrial Internet Reference Architecture (IIRA): Developed by the US-led Industrial Internet Consortium, this manufacturing-oriented architecture promotes the global adoption of the Industrial Internet of Things (IIoT) (Boyes et al., 2018).

2. Industrial Value Chain Reference Architecture (IVRA): A conceptual framework maintained by the Industrial Value Chain Initiative in Japan.
3. Stuttgart IT Architecture for Manufacturing (SITAM): A multi-layered architecture from research projects led by the University of Stuttgart, Germany (Kassner et al., 2017).
4. LAsim Smart FActory (LASFA): A three-dimensional architecture proposed by the University of Ljubljana, Slovenia (Resman et al., 2019).
5. IBM Industry 4.0: A commercially distributed architecture.
6. Reference Architectural Model Industrie 4.0 (RAMI4.0): A domain-specific architecture guided by the German government through the international technical specification IEC PAS 63088:2017 (Adolphs et al., 2015).

According to Nakagawa et al. (2021), RAMI4.0 is the most studied and prevalent reference architecture, as evidenced by research in Scopus and Web of Science. It facilitates I4.0 applications by providing a framework for integrating components and products across networks (Veiga et al., 2021). Çınar et al. (2021) evaluated RAMI4.0's maturity concerning I4.0 implementation, exploring solutions to optimize the utilization of I4.0 technologies.

The RAMI4.0 encompasses essential components structured around three dimensions: (1) life cycle and value stream, (2) layers, and (3) hierarchy levels (International Electrotechnical Commission, 2017). The life cycle and value stream dimension represent the industrial production process, detailing product development and production stages. This dimension includes two phases: 'type'—for products in development—and 'Instance'—for products in production. Products revert to the type of phase upon customer purchase and again to the Instance phase when installed in a system.

The RAMI4.0 outlines several key layers:

1. Business Layer: Maps business models and processes, establishing rules and regulations aligned with corporate strategy.
2. Functional Layer: Describes, models, and formally integrates services and activities.
3. Information Layer: Facilitates event preprocessing, rule execution, data analysis, and quality assurance.
4. Communication Layer: Enables communication and provides control services.
5. Integration Layer: Connects physical objects to the digital realm through information processing, offering insights about assets and enabling control and event generation.
6. Asset Layer: Represents the physical components within a factory.

The hierarchical manufacturing levels are informed by international standards for corporate control system integration (IEC 62264 and IEC 61512) (Adolphs et al., 2015). At the bottom, the Field Device layer enables intelligent control of machinery through smart sensors, ensuring a consistent view of the product and its interdependencies. Conversely, the connected world layer at the top symbolizes the smart factory's capacity to engage with external partners via collaborative service networks. A notable feature of the RAMI4.0 is its combination of life cycle and value stream with a hierarchical approach to defining I4.0 components (Dorst et al., 2016). The architecture emphasizes the standardization of I4.0 components, such as products, assets, software, or machines, that can communicate independently (Pedone & Mezgár, 2018).

To effectively manage PSM, advanced I4.0 technologies are increasingly crucial. These include Blockchain for smart contracts (Dutta et al., 2020), RFID for material tracking (Gladysz et al., 2020), Power BI for interactive visualizations and business analytics (Wright & Wernecke, 2020), Internet of Things (Glas & Kleemann, 2016), predictive analytics and big data (Schoenherr & Speier-Pero, 2015), ERP and mobile solutions (Pavin & Klein, 2015), e-procurement systems for collaboration (Alvarez-Rodríguez et al., 2014), and web-based digital technologies (Gallear et al., 2008).

These technologies are poised to enhance PSM, fostering a smarter, more interconnected supply chain ecosystem. Potential applications for emerging I4.0 technologies within the supply chain include sustainability (Manavalan & Jayakrishna, 2019), procurement (Glas & Kleemann, 2016), logistics (Hopkins & Hawking, 2018), customer relationship management (Saucedo-Martínez et al., 2018), storage (Lee et al., 2018), and supply chain optimization (Tjahjono et al., 2017). This article leverages the RAMI4.0 framework to illustrate enhancements in PSM (Riedmann et al., 2024).

3. Case study methodology

This study adopted a qualitative single-case study approach within the PSM department of a Brazilian long carbon steel company. The case study methodology, as outlined by Voss et al. (2002), was selected for its comprehensive framework, which is particularly well-suited for in-depth investigation of complex, real-world phenomena. In accordance with the case study research methodology proposed by Voss et al. (2002), this study followed the structured steps for conducting case research, ensuring rigor and consistency throughout the research process. These steps included: (1) When to use case research, (2) Developing the research frameworks, constructs, and questions, (3) Choosing cases, (4) Developing research instruments and protocols, (5) Conducting the field research, (6) Data documentation and coding, (7) Data analysis, hypothesis development, and testing. The research methodology followed the approach of Voss et al. (2002) and was structured as follows: the first step focused on choosing the case study, reviewing the literature, document analysis and interviews, focus group with the PSM team, strategic focus group with the leadership team, and data analysis, and testing. These phases are illustrated in Figure 1.

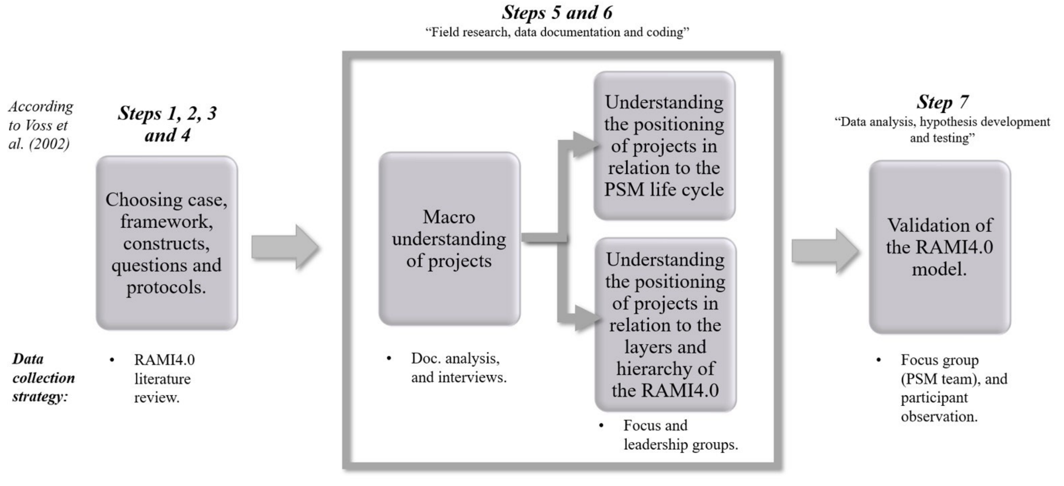

Figure 1. Case study approach according to Voss et al. (2002).

The first four phases of the case study approach, according to Voss et al. (2002), were carried out through the structuring of the research, including the stages of case selection, framework, constructs, questions, and protocols. The data collection instrument used was the literature review. The selected company is one of the largest carbon steel producers globally. In addition to its relevance, the company is in the process of digitalizing the PSM, implementing several projects aimed at transitioning to Industry 4.0. The relevance of the context to the research object, along with the company's openness to the study, together justify the selection of this case as the focus of the research. The PSM department presents a certain level of complexity, given its diverse business divisions—mining, bioforestry, steel production, and wire drawing—and multiple units distributed across Brazil. The justification for the choice of this company was primarily due to the ease of access and the opportunity to conduct a study that would provide in-depth insights into the PSM within the steel unit. Various data collection methods were employed from a longitudinal perspective over several months. This high level of access allowed for the gathering of data with a broad scope, which contributed significantly to the results and analysis presented in this article.

The hierarchical structure of the PSM includes a national director, three general managers responsible for specific purchasing categories, local plant managers, analysts, and purchasing and warehouse technicians. The total number of PSM employees nationwide is approximately 320.

The PSM board features a central office responsible for negotiating contracts at the national level. This team manages common contracts among the plants, covering areas such as energy, raw materials, spare parts, and services, to achieve synergy and economies of scale.

Within each steel plant, the PSM is divided into two teams: (1) purchasing team: Responsible for quotations, negotiations, track orders and local contracting of emergency and non-contract items—those not covered by central contracts and (2) warehouse team: manages processes related to receiving, checking, storing, invoicing, and distributing materials.

Following steps 1 to 4 of the research, three cycles were carried out, which involved conducting the field research (phase 5) and documenting and coding the data (phase 6). The first cycle aimed at a macro understanding of the projects, the second focused on understanding the positioning in relation to the life cycle, and the third, finally, concentrated on the layers and hierarchy.

For the macro understanding of projects and their strategic objectives, data collection was carried out, employing three combined methods: document analysis, interviews, focus groups and participant observation.

Document Analysis involved the examination of the document entitled *Strategic supply planning – Long carbon steel Brazil 2022*. Six strategic projects related to the adoption of I4.0 in PSM were identified: (1) Strategic sourcing methodology, (2) RFID system implementation, (3) Implementation of technical inspection, (4) Automatic invoice release, (5) Optimization of delivery points at the plant, and (6) Restructuring of the warehouse layout. Through the analysis of this document, it was possible not only to identify the various projects but also to delineate their objectives, the technologies employed, the categories of materials explored (i.e., raw materials or spare parts), and the anticipated outcomes. This facilitated a clearer and more precise understanding of the strategies adopted. Such insights were crucial for extracting relevant information from the strategic projects within the PSM area, thereby enabling a comprehensive examination of the decisions and actions implemented over time.

The interviews were essential for gathering detailed information on the operationalization of the projects. During this phase, interviews were conducted with supply analysts directly involved in the projects, as well as with managers, to ensure the accuracy and completeness of the information collected. This process enabled a deeper understanding of how the initiatives would be implemented in daily activities. Interaction with these professionals provided valuable insights into the challenges faced, the practices adopted, and the strategies required for the successful execution of the projects. The approach was particularly productive, as it allowed for a more detailed analysis of the operational dynamics, while also identifying critical factors that directly impact the success of project implementation, considering the specific context of each area. The interviews were guided by two set of questions, with the purpose of verify: (1) What is the strategic relevance of each project? and (2) What positive outcomes are expected following the implementation of the projects?

The research questions were formulated according to the objectives of each phase of the study: initially, to characterize the projects in question, and later, with the aim of positioning these projects within the different dimensions of the RAMI 4.0 model. Most interviews were conducted online due to geographical constraints, while others took place in person based on the interviewees' availability. Each interview lasted an average of 45 minutes, with some requiring multiple sessions to address the complexity of certain projects. The interviews were recorded, transcribed, and subsequently analyzed. The analysis of the transcriptions played a crucial role in completing the project characterization tables. The transcription process was carried out with meticulous attention to detail, ensuring the accuracy and fidelity of the collected data. Based on these transcriptions, a qualitative analysis was carried out, applying thematic coding to identify patterns and group the data into predefined categories, such as objectives, technologies used, materials explored, and expected results. This process enabled a structured organization of the information, ensuring a clear and precise characterization of the projects. Additionally, the extracted information was verified, whenever possible, with other sources, such as document analysis, ensuring the consistency and robustness of the data.

For the second cycle, which focused on understanding the positioning in relation to the life cycle, and the third, which examined the positioning in relation to the layers and hierarchy, the data were collected and analyzed separately and concurrently within the appropriate dimensions of the RAMI4.0 within the context of PSM. To achieve this, we used a focus group format, and asked the following questions related to the dimension of life cycle: (1) Considering the project under your responsibility, in which phase of the life cycle is it? and (2) In which layer does it fall? It was clarified that the life cycle dimension encompasses the stages of PSM, which include purchasing and warehouse management.

For the layer dimension, we asked: (1) Considering the project under your responsibility, in which layer is it? and (2) In which layer does it fall? Regarding the RAMI4.0 layers in the context of PSM, these are categorized as: physical world, integration, information/communication, and business. For the hierarchy dimension, we asked: (1) Considering the project under your responsibility, in which hierarchy level is it? and (2) In which layer does it fall? The focus group strategy proved to be highly effective in positioning the projects within the appropriate dimensions.

Finally, the step seven, data analysis, hypothesis development and testing, the model was evaluated through a focus group comprising three supply managers, one warehouse manager, six supply analysts, and three supply technicians. The focus group was conducted in a workshop format, employing a brainstorming approach. Since the focus groups were organized based on similarities, that is, according to the professionals' areas of expertise and the applicability of the projects, this stage proved to be highly productive. This group included representatives from all projects (see Table 1). During the workshop, the participant observation strategy was also employed to assess the applicability of the three-dimensional model in accordance with the RAMI4.0 framework. This stage was conducted remotely, lasted one hour, and included two guiding questions:

Table 1. List of projects and participants by job positions.

Strategic Project	Interviews / Focus group (leadership)			Evaluation of RAMI4.0 model
	Participants	1° phase	2° phase	
Strategic Sourcing Methodology	02 - Supply Managers, 01 - Warehouse Manager, 06 - Supply analysts, and, 03 – supply technicians.	42 min online	38 min online	Participation of over 12 professionals from the supply department. Duration: 01 hour. Online
Implementation of technical inspection		55 min	35 min	
Restructuring of the warehouse layout		58 min	32 min online	
Automatic invoice release		39 min	30 min online	
RFID System Implementation		52 min online	30 min online	
Optimization of delivery points at the Plant		45 min online	33 min	

1. Considering the positioning of projects according to the three dimensions of RAMI4.0 presented, what adjustments do you consider important to implement?
2. What effective gains for PSM do you expect each project to present?

The research was developed across five stages, facilitating the triangulation and comparison of the collected data. In the early stages, data gathered through various research methods, such as direct observation, document analysis, and interviews, provided a deeper understanding of the projects' context and operational realities. Furthermore, the data collected from focus groups, especially the final session, enabled a comparative analysis, allowing for the validation and corroboration of the initial findings with key stakeholders involved in the different projects.

4. Results

This section presents the qualitative results that supported the characterization of the proposed RAMI4.0 model.

4.1. The PSM of the steel company and the strategic projects analyzed

To characterize the six strategic projects of the PSM department Table 2 was prepared. This table presents the purpose, strategic objective, the purchasing category involved and the technologies for each project.

4.2. Positioning of PSM projects in the RAMI4.0 Life Cycle dimension

From the structuring of Table 2, it was possible to unfold the actions and resources necessary for the development and implementation of projects. It was observed that only one project is aimed exclusively at the raw material category, three are exclusive to spare parts and two involve both categories. The company's enterprise resource planning (ERP) system was considered an information system that relates to other technologies involved in different projects.

The positioning of PSM projects according to the life cycle dimension of RAMI4.0 was based on two macroprocesses: the purchasing process and warehouse management. As discussed in the literature review on PSM, the purchasing function represents the commercial aspect and the relationship with suppliers, while the warehouse function pertains to the physical management of materials acquired by the company. It is noteworthy that, although RAMI4.0 is typically applied to the positioning of projects and technologies in manufacturing. This study utilized it to position the PSM function projects within a steel company.

The purchasing process is presented linearly, based on the emergence of demand for acquiring materials or services. This demand is communicated by the internal customer areas of the steel plants. Once the purchase request or requisition is approved, the purchasing flow commences. The stages of the purchasing process include:

Table 2. Characterization of the projects analyzed.

Strategic Project	Purpose of the Strategic Project	Strategic Objective	Purchase Category Involved	Technologies by project
Strategic sourcing methodology	Technical and strategic assessment of the company's supply sources. Opening of frequent competition to identify the best suppliers that qualify in the following aspects: cost, risk and benefit.	Increase contractual coverage in the acquisition of materials; and Reduce operational risks of interruptions and shortages.	Raw materials and spare parts	Power BI, Analytics, ERP
Implementation of technical inspection	Point-to-point traceability of raw material stocks at plants.	Eliminate manual controls in the transfer of raw materials.	Raw materials	Tags with chip, antennas, ERP
Restructuring of the warehouse layout	Assessment of spare parts regarding the expected level of quality requirements.	Ensure compliance (quality) of critical inventory items.	Spare parts	QR code, mobile, ERP
Automatic invoice release	Automation of manual activity.	Increase productivity and assertiveness of this process.	Spare parts	ERP
RFID system implementation	Standardization of material delivery points at plants.	Increase productivity in the distribution and delivery of materials from the warehouse to the requesting areas.	Spare parts	Smart locker, biometry, ERP
Optimization of delivery points at the Plant	Optimization of physical warehouse space and intelligent storage based on packaging characteristics/dimensions and stock turnover criteria.	Optimize storage spaces/physical spaces.	Raw materials and spare parts	Simulation, ERP

(1) quotation (market consultation or opening of competition); (2) negotiation (reopening negotiation rounds to achieve cost reductions); (3) contracting (finalizing the competition and issuing the order or purchase contract); and (4) monitoring the order until it arrives at the requesting plant.

The warehouse process was divided into four steps: (1) receiving and checking materials; (2) storage (allocating items in stock according to a pre-defined position for each material); (3) invoice release (recording the order entry); and (4) distribution, which encompasses delivering the material to the requesting area. Based on these stages from the two macroprocesses, the projects were positioned within the life cycle according to the stages they would impact. The result of this positioning is illustrated in Figure 2.

Considering the prioritized projects, it is important to note that some stages of PSM were not addressed by these projects, resulting in some cells in Figure 2 remaining unfilled. Certain projects are specific to the raw materials category, while others pertain specifically to spare parts. In instances where projects apply to both categories, the corresponding table cells were merged to encompass both categories presented. Notably, there is only one project related to the purchasing process.

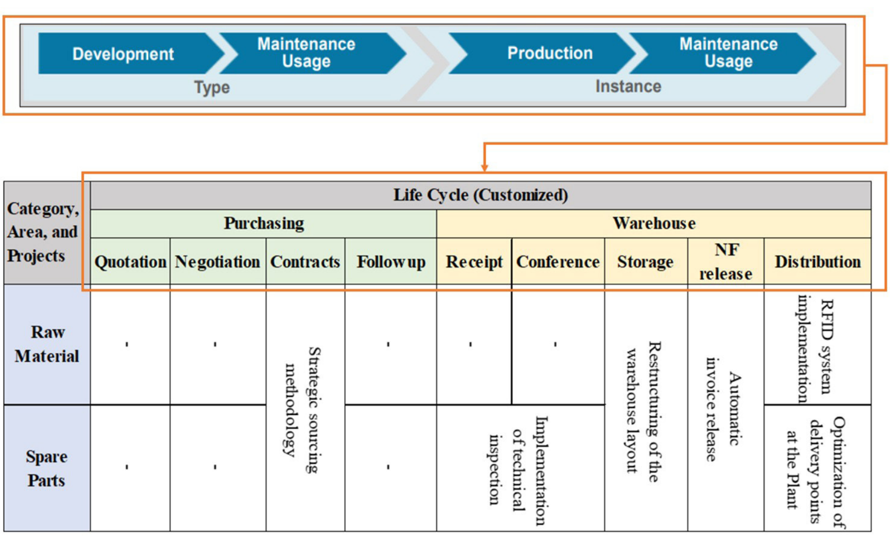

Figure 2. Positioning of projects in relation to the life cycle dimension (customized).

4.3. Positioning of PSM projects in the layers dimensions of the RAMI4.0

The positioning of projects within the layers dimension of the RAMI4.0 followed the same reasoning as that of the life cycle dimension. For each layer of the RAMI4.0, strategic projects were identified along with the purchasing category involved in each project (raw materials or spare parts), as presented in Table 3. The impacts and strategic relevance of each project were considered when determining their positions within the layers.

Table 3. Positioning of projects in relation to the layers dimension.

Layers	Strategic Project	PSM Category Involved
Business	Strategic sourcing methodology	Raw materials and spare parts
Information / Communication	Implementation of technical inspection	Spare parts
	Restructuring of the warehouse layout	Raw materials and spare parts
	Automatic invoice release	Raw materials and spare parts
Integration	RFID system implementation	Raw materials
	Optimization of delivery points at the plant	Spare parts
Physical world	-	Raw materials and Spare parts

The project "Strategic sourcing methodology" was classified as a strategic initiative that significantly influences the company's business, given that strategic supply contracts and partnerships have substantial potential for establishing new contracts and revising existing ones. Consequently, this project was positioned at the business layer. The other projects were deemed tactical, as they relate to important processes and productivity improvements but do not qualify as strategic initiatives. Therefore, they were positioned in the middle layers of the reference architecture. Notably, no project was confined to the physical world layer.

The physical layer is the foundational layer, traditionally represented by the asset, product, or process in the RAMI4.0. In the present study, this layer is understood as the purchased materials, specifically raw materials or spare parts. This layer represents the physical world. The integration layer, in turn, was interpreted as the integration of these materials into the digital world. This layer highlights which systems and/or devices are available to facilitate the digitization of processes. The information/communication layer is where access to information is emphasized, showcasing how data flows and is managed between various systems. Finally, the business layer is represented by the supply management strategy, encompassing broader strategic decisions that guide procurement and supply chain management efforts.

4.4. Positioning of PSM projects in the hierarchy dimensions of the RAMI4.0

The hierarchy dimension was analyzed based on the conceptual framework of the RAMI4.0. This dimension is composed of flexible systems and functions distributed across the network, allowing all stakeholders and components involved to communicate effectively with each other. According to Table 4, data collected in the research were mapped to each hierarchical level of the RAMI4.0, from the lowest product level to the highest connected world level.

Table 4. Positioning of projects in relation to the hierarchy dimension.

<table>
<tr><th colspan="6">PSM Strategic Projects</th><th rowspan="2">Hierarchy</th></tr>
<tr><th>Strategic sourcing methodology</th><th>Implementation of technical inspection</th><th>Restructuring of the warehouse layout</th><th>Automatic invoice release</th><th>RFID system implementation</th><th>Optimization of delivery points at the Plant</th></tr>
<tr><td colspan="6">-</td><td>External / connected world</td></tr>
<tr><td>X</td><td colspan="5">-</td><td>Company</td></tr>
<tr><td colspan="6">X</td><td>Work stations</td></tr>
<tr><td>-</td><td>X</td><td>-</td><td>-</td><td>X</td><td>-</td><td>Field / control devices</td></tr>
<tr><td colspan="6">X</td><td>Product</td></tr>
</table>

It was observed that no project was positioned at the external/connected world level, as the analyzed projects are primarily focused on the internal management of the company's PSM processes. The scope of these projects remains within the internal organizational boundaries, without extending to external collaborative networks or partnerships at the connected world level.

4.5. Representation of the RAMI4.0 model

To characterize the RAMI4.0 model within the context of this research, it was crucial to cross-reference its three dimensions, life cycle, layers, and hierarchy, with the specific projects and technologies currently implemented within the studied steel group. This cross-referencing process is illustrated in Figure 3. The life cycle dimension encompasses the various stages of PSM, with a particular focus on both the purchasing and warehouse functions. The purchasing stage was further subdivided into distinct phases: quote, negotiation, contracts, and follow-up, aligning with the divisions identified in the research context.

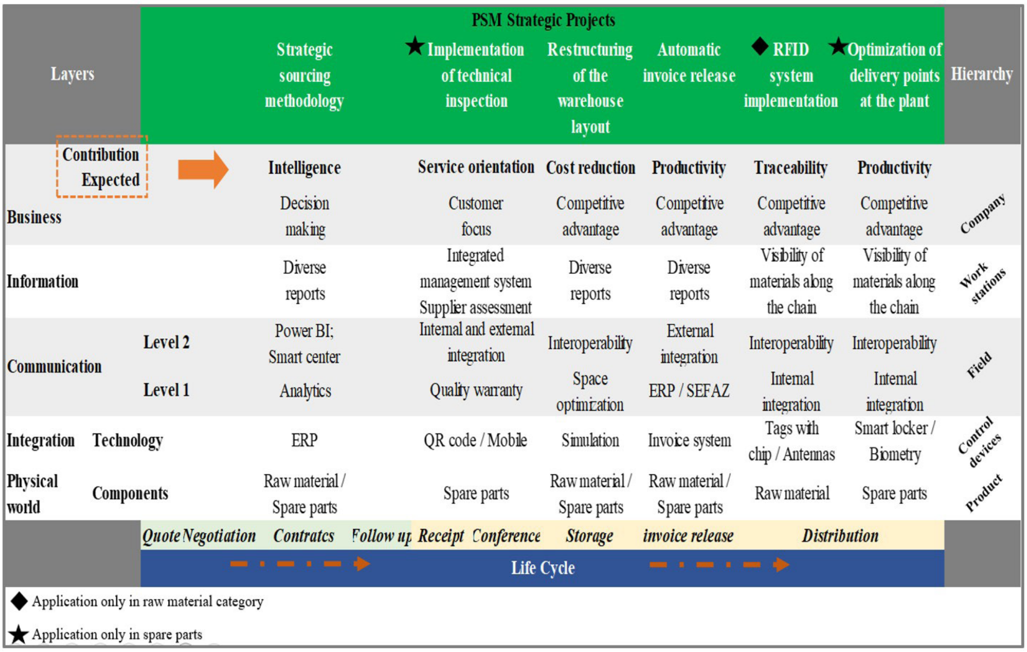

Figure 3. Positioning of projects in the RAMI4.0 framework.

The layer dimension outlines the decision-making levels involved in each project, categorizing them as strategic, tactical, or operational. For example, the layers associated with the "Implementation of Technical Inspection" project illustrate its operations within the physical world, specifically concerning spare parts, starting directly at the receipt stage. A key aspect to highlight is the expected contribution of these projects to the overall PSM function. This contribution is prominently featured at the top of reference architecture, just above the business layer, emphasizing the strategic value these initiatives bring to the organization.

An interesting aspect of the projects is that, although they are strategic for the PSM board, the business layer reveals that most decisions are operational and tactical, with process-level indicators. Only one project, the "Strategic sourcing methodology", involves strategic decision-making. The supply manager stated that: "*The implementation of strategic sourcing will be essential to optimize the efficiency of procurement processes, reduce costs, improve supplier quality, and align purchasing with the organization's strategic objectives*". In the information/communication layer, the ERP system stands out as the main source of information access. The Power BI system, also positioned in this layer, helps generate patterns for analysis and decision-making. Other integrated management systems and simulation software also appear in this layer.

In the integration layer, the ERP system again plays a key role, particularly in operational record-keeping. The QR code/mobile system has proven fundamental for technical inspection in the "Implementation of Technical Inspection" project and for the "RFID system implementation" project. Data collection in this project is carried out with the aid of RFID tags with chips and antennas throughout the warehouse, enabling precise tracking of material movements. The warehouse manager stated: "*With the RFID project, we will increase accuracy in inventory control, reduce operational errors, improve item traceability, and optimize logistical processes, aligning with the operational needs for efficiency and agility*". In the "Optimization of delivery points at the plant" project, a technology known as smart locker is used. This system verifies receipt through the biometric confirmation of the material requester.

In the hierarchy dimension, most indicators suggest that projects are concentrated at the process level within purchasing and warehouse operations, mainly at the workstation level. Only the "Strategic sourcing methodology" project impacts the business level, as it involves strategic contract decisions. Projects such as "Implementation of technical inspection" and "RFID system implementation" are positioned at the Field/Control Devices level, focusing on spare parts control, raw material quality, and stock accuracy.

In summary, integrating the three dimensions of the RAMI4.0 into the PSM context enables the standardization of processes, from the design phase to solution implementation. Across all layers, operational records, data collection, and data consolidation between management systems and ERP auxiliary interface systems were observed. The ERP system connects the physical and virtual worlds, meeting the company's integration standards. Below the ERP, data collection capabilities have increased significantly, using sensors, QR codes, and RFID systems. Above the ERP, tools like Power BI and analytics enhance pattern recognition and decision-making capabilities.

5. Discussion

This section presents the theoretical and practical contributions of the work.

5.1. Contributions to theory

This article makes two significant contributions. The first contribution is the adaptation of the RAMI4.0 framework to the context of PSM, a model originally designed for manufacturing applications (Grefen et al., 2022; Çınar et al., 2021; Murugaiyan & Ramasamy, 2021; Lins & Oliveira, 2020; Resman et al., 2019; Yli-Ojanpera et al., 2019). This adaptation broadens the scope of RAMI4.0's application, extending it beyond manufacturing to address all four dimensions of Industry 4.0: work, product, manufacturing, and supply chain. Specifically, the study reconfigures the life cycle dimension, which was originally centered on product development and manufacturing, to encompass PSM processes, including purchasing and warehouse functions, along with their respective stages. By integrating these dimensions, this work opens new avenues for research, particularly in the domain of smart supply chains. It underscores the potential for further exploration of how the RAMI4.0 framework can facilitate the coordination and optimization of supply chain activities within the Industry 4.0 paradigm.

The second contribution is the empirical evaluation of the adapted reference architecture within a steel plant. Using the RAMI4.0 framework, the study assessed the alignment of PSM projects with its three core dimensions: life cycle, layers, and hierarchy. In doing so, the study not only mapped the coverage of these projects but also identified and categorized the technologies implemented at various stages, organizing them according to the RAMI4.0 structure. This analysis provides insight into how digital transformation is unfolding within the organization, demonstrating how the integration of advanced technologies across both the life cycle and hierarchical layers is driving the evolution of industrial processes in accordance with Industry 4.0 principles. The study offers a framework that illustrates the digital transformation of a company's PSM function, thereby bridging two previously disparate areas of literature: PSM (Pereira et al., 2020; Schütz et al., 2020; van Weele, 2009) and RAMI4.0 (Çınar et al., 2021).

5.2. Contributions to practice

In terms of practical implications, the proposed three-dimensional architecture offers PSM professionals a comprehensive framework to assess the alignment of strategic projects with the adoption of Industry 4.0 (I4.0) within the PSM function. This framework allows professionals to tailor strategies to the specific needs and context of their company. Another significant aspect is the instrumental perspective provided by the reference architecture, which links the implementation of each project to the tangible benefits it generates. The results highlight that the adoption of I4.0 strategies within the PSM function is primarily driven by critical factors such as productivity enhancement, cost reduction, agility, traceability, service orientation, and intelligence.

The representation of the projects within the proposed architecture facilitated their consolidation into a unified conceptual framework, offering extensive coverage that spans from the physical layer (data collection) to the decision-making level. The technologies implemented in these projects support decision-making across a spectrum, from operational to strategic levels. Furthermore, a distinction was observed in the applicability of specific projects to two distinct material types: raw materials and spare parts. This differentiation highlights the tailored approach required for each material type, reflecting the diverse operational needs within the PSM function.

The analysis of the most applied I4.0 technologies in spare parts management reveals distinct differences when compared to raw material management. Notably, certain projects tailored for spare parts are not applicable to raw materials, apart from the “RFID system implementation” project, which is being considered for potential use in both contexts. These differences arise from the unique challenges associated with managing spare parts, which require more stringent control, tracking, and generate a higher volume of information. For example, the “Implementation of technical inspection” project is particularly relevant to spare parts, as it ensures the conformity and quality of items received into inventory. In contrast, raw materials do not necessitate such inspections, as they are subject to laboratory testing through sampling. Conversely, the “RFID system implementation” project is more critical for raw materials due to their continuous flow and the large volumes involved in their packaging and transfer. The application of RFID technology in this context will greatly enhance control and traceability over raw material transfers. Finally, the “Optimization of delivery points at the plant” project is focused on managing the complexity of multiple delivery and unloading points, making it specific to the spare parts context. Consequently, the adoption of I4.0 technologies in PSM is closely linked to the type of product being managed, with different strategies and technologies tailored to the specific characteristics and requirements of spare parts versus raw materials.

6. Conclusions

The RAMI4.0 framework was selected for this research due to its flexibility in adaptation across various industry applications and the extensive availability of supporting study materials. RAMI4.0 is the most frequently referenced architecture in academic literature, as evidenced by a comparative search in major research databases such as Scopus and Web of Science. A search using the term “RAMI 4.0” yielded 262 documents, while alternative architectures generated fewer than 20 results (Nakagawa et al., 2021). This widespread recognition and application in the literature underscore RAMI4.0’s prominence and establish it as a consolidated reference in the field, in contrast to other architectural models. As noted by Adolphs et al. (2015), RAMI4.0 integrates several critical concepts, including vertical and horizontal integration, end-to-end engineering, and life cycle management, making it a comprehensive framework for addressing Industry 4.0 challenges.

The objective of this research “to characterize PSM projects developed in the context of I4.0 at a Brazilian steel company, using the RAMI4.0 model” was successfully achieved through the adaptation of this architecture to the PSM function. The study illustrates that the RAMI4.0 model, originally designed for the purpose of modeling I4.0 technologies in manufacturing systems, can be extended beyond its initial scope to support other organizational functions, such as PSM. This adaptation not only broadens the applicability of the RAMI4.0 model but also demonstrates its potential to optimize and integrate diverse business processes within the industry 4.0 paradigm.

To provide a comprehensive understanding of technological architecture, this study thoroughly examined the structure, information and communication flows, software systems, and their interconnections. The ERP system played a pivotal role in the digitalization process, facilitating the integration of data across various technologies. Furthermore, the research revealed that the integration of external software and platforms with the ERP system generates critical records and analytical patterns, which are instrumental in supporting informed decision-making processes. This integration enhances the overall effectiveness of the technological ecosystem, enabling more seamless operations and improved strategic outcomes.

Figure 3, which illustrates the positioning of projects within the RAMI4.0 framework, demonstrates the central role of the ERP system within the integration and information/communication layers. Upon analyzing the life cycle dimension, which encompasses the various stages of the PSM process, it becomes evident that the ERP system is present throughout all stages. In the hierarchy dimension, the ERP system is also integral as both a control device and at the workstation level, underscoring its pivotal role in the implementation of I4.0 projects. This positioning highlights the ERP system’s critical function in facilitating the seamless flow of information and enhancing decision-making processes across multiple levels of the organization.

As with any research, there are limitations. Only six projects were evaluated, all pre-defined by the PSM department. Future research should explore additional strategic projects within the PSM function to provide a more comprehensive roadmap for professionals seeking to adopt I4.0 in PSM.

Finally, regarding the management systems that support the digitalization of the PSM function, it is widely recognized that these systems drive digitalization within companies. The company analyzed in this study employs business intelligence systems as its technological architecture, but future studies could explore alternative systems and architectures to better understand the role of digitalization in PSM across different contexts and companies.

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Data availability

The data that support the findings of this study are available in the body of the article.

References

Adolphs, P., Bedenbender, H., Dirzus, D., Ehlich, M., Epple, U., Hankel, M., Heidel, R., Hoffmeister, M., Huhle, H., Kärcher, B., Koziolek, H., Pichler, R., Pollmeier, S., Schewe, F., Walter, A., Waser, B., Wollschlaeger, M., & Wollschlaeger, M. (2015). *Reference Architecture Model Industrie 4.0 (RAMI 4. 0): status report.* Berlin: ZVEI.

Alvarez-Rodríguez, J. M., Labra-Gayo, J. E., & de Pablos, P. O. (2014). New trends on e-Procurement applying semantic technologies: current status and future challenges. *Computers in Industry*, *65*(5), 800-820. http://doi.org/10.1016/j.compind.2014.04.005.

Bals, L., Schulze, H., Kelly, S., & Stek, K. (2019). Purchasing and supply management (PSM) competencies: current and future requirements. *Journal of Purchasing and Supply Management*, *25*(5), 100572. http://doi.org/10.1016/j.pursup.2019.100572.

Boyes, H., Hallaq, B., Cunningham, J., & Watson, T. (2018). The industrial internet of things (IIoT): an analysis framework. *Computers in Industry*, *101*, 1-12. http://doi.org/10.1016/j.compind.2018.04.015.

Caiado, R. G. G., Scavarda, L. F., Azevedo, B. D., Mattos Nascimento, D. L., & Quelhas, O. L. G. (2022). Challenges and benefits of sustainable industry 4.0 for operations and supply chain management: a framework headed toward the 2030 agenda. *Sustainability*, *14*(2), 830. http://doi.org/10.3390/su14020830.

Caldas, N., Sousa, J. P., Alcalá, S. G., Frazzon, E., & Moniz, S. (2019, July). A simulation approach for spare parts supply chain management. In *Proceedings of the International Conference on Industrial Engineering and Operations Management* (pp. 23-26). Southfield: IEOM Society International.

Carnovale, S., & DuHadway, S. (2021). Continuity in the face of disruptions: purchasing and supply management research's persistence amidst COVID-19. *Journal of Purchasing and Supply Management*, *27*(4), 100720. http://doi.org/10.1016/j.pursup.2021.100720.

Chartered Institute of Procurement & Supply – CIPS. (2020). Retrieved in 2024, February 6, from https://www.cips.org/en-gb/cips-for-individuals/what-is-procurement//

Çınar, Z. M., Zeeshan, Q., & Korhan, O. (2021). A framework for industry 4.0 readiness and maturity of smart manufacturing enterprises: a case study. *Sustainability*, *13*(12), 6659. http://doi.org/10.3390/su13126659.

Cousins, P. D., Lawson, B., & Squire, B. (2006). An empirical taxonomy of purchasing functions. *International Journal of Operations & Production Management*, *26*(7), 775-794. http://doi.org/10.1108/01443570610672239.

Crespi, G., Criscuolo, C., & Haskel, J. (2007). *Information technology, organisational change and productivity.* London: CEPR Press.

Dorst, W., Glohr, C., Han, T., Knafla, F., Loewen, U., Rosen, R., Schiemann, T., Vollmar, F., & Winterhalter, C. (2016). *Implementation strategy industrie 4.0: report on the results of the industrie 4.0 platform.* Albrechtstraße: Bitkom.

Dutta, P., Choi, T. M., Somani, S., & Butala, R. (2020). Blockchain technology in supply chain operations: applications, challenges and research opportunities. *Transportation Research Part E, Logistics and Transportation Review*, *142*, 102067. http://doi.org/10.1016/j.tre.2020.102067. PMid:33013183.

Fernandes, J. C. M., Silva, S. E., & Reis, L. P. (2021, September). Roadmap for the adoption of smart supply chain. In *European Conference on Innovation and Entrepreneurship* (pp. 1254-1263). London: Academic Conferences International Limited.

Fernandes, J., Reis, L. P., & Silva, S. E. (2023). Digital supply chain: Roadmap development and application based on Industry 4.0 principles. *IFAC-PapersOnLine*, *56*(2), 10339-10344. http://doi.org/10.1016/j.ifacol.2023.10.1044.

Frank, A. G., Dalenogare, L. S., & Ayala, N. F. (2019). Industry 4.0 technologies: Implementation patterns in manufacturing companies. *International Journal of Production Economics*, *210*, 15-26. http://doi.org/10.1016/j.ijpe.2019.01.004.

Frazzon, E. M., Holtz, T. H., Silva, L. S., & Pires, M. C. (2019). Simulation-based analysis of intelligent maintenance systems and spare parts supply chains integration. *Journal of Intelligent Systems*, *28*(1), 31-42. http://doi.org/10.1515/jisys-2016-0303.

Frohlich, M. T., & Westbrook, R. (2001). Arcs of integration: an international study of supply chain strategies. *Journal of Operations Management*, *19*(2), 185-200. http://doi.org/10.1016/S0272-6963(00)00055-3.

Gajdzik, B., & Wolniak, R. (2021). Transitioning of steel producers to the steelworks 4.0: literature review with case studies. *Energies*, *14*(14), 4109. http://doi.org/10.3390/en14144109.

Gallear, D., Ghobadian, A., & O'Regan, N. (2008). Digital/web-based technology in purchasing and supply management: a UK study. *Journal of Manufacturing Technology Management*, *19*(3), 346-360. http://doi.org/10.1108/17410380810853777.

Garay-Rondero, C. L., Martinez-Flores, J. L., Smith, N. R., Morales, S. O. C., & Aldrette-Malacara, A. (2020). Digital supply chain model in Industry 4.0. *Journal of Manufacturing Technology Management*, *31*(5), 887-933. http://doi.org/10.1108/JMTM-08-2018-0280.

Gladysz, B., Ejsmont, K., Kluczek, A., Corti, D., & Marciniak, S. (2020). A method for an integrated sustainability assessment of rfid technology. *Resources*, *9*(9), 107. http://doi.org/10.3390/resources9090107.

Glas, A. H., & Kleemann, F. C. (2016). The impact of industry 4.0 on procurement and supply management: a conceptual and qualitative analysis. *International Journal of Business and Management Invention*, *5*(6), 55-66.

Grefen, P., Vanderfeesten, I., Traganos, K., Domagala-Schmidt, Z., & van der Vleuten, J. (2022). Advancing smart manufacturing in europe: experiences from two decades of research and innovation projects. *Machines*, *10*(1), 45. http://doi.org/10.3390/machines10010045.

Hermann, M., Pentek, T., & Otto, B. (2016, January). Design principles for industrie 4.0 scenarios. In *2016 49th Hawaii International Conference on System Sciences (HICSS)* (pp. 3928-3937). New York: IEEE.

Hopkins, J., & Hawking, P. (2018). Big Data Analytics and IoT in logistics: a case study. *International Journal of Logistics Management*, *29*(2), 575-591. http://doi.org/10.1108/IJLM-05-2017-0109.

Instituto Aço Brasil – IAB. (2023). *Estatísticas da Siderurgia 4º Trimestre 2023*. Rio de Janeiro: IAB.

International Electrotechnical Commission – IEC. (2017). *IEC PAS 63088:2017: smart manufacturing: reference architecture model Industry 4.0 (RAMI4.0).* London: IEC.

Ivanov, D., Dolgui, A., & Sokolov, B. (2022). Cloud supply chain: Integrating Industry 4.0 and digital platforms in the "Supply Chain-as-a-Service". *Transportation Research Part E, Logistics and Transportation Review*, *160*, 102676. http://doi.org/10.1016/j.tre.2022.102676.

Kassner, L., Gröger, C., Königsberger, J., Hoos, E., Kiefer, C., Weber, C., Silcher, S., & Mitschang, B. (2017). The Stuttgart IT architecture for manufacturing: an architecture for the data-driven factory. In *Enterprise Information Systems: 18th International Conference, ICEIS 2016* (pp. 53-80). Cham: Springer International Publishing. http://doi.org/10.1007/978-3-319-62386-3_3.

Khajavi, S. H., Partanen, J., & Holmström, J. (2014). Additive manufacturing in the spare parts supply chain. *Computers in Industry*, *65*(1), 50-63. http://doi.org/10.1016/j.compind.2013.07.008.

Lee, C. C. (2006). Two-warehouse inventory model with deterioration under FIFO dispatching policy. *European Journal of Operational Research*, *174*(2), 861-873. http://doi.org/10.1016/j.ejor.2005.03.027.

Lee, C. K., Lv, Y., Ng, K. K., Ho, W., & Choy, K. L. (2018). Design and application of Internet of things-based warehouse management system for smart logistics. *International Journal of Production Research*, *56*(8), 2753-2768. http://doi.org/10.1080/00207543.2017.1394592.

Legenvre, H., Henke, M., & Ruile, H. (2020). Making sense of the impact of the internet of things on Purchasing and Supply Management: A tension perspective. *Journal of Purchasing and Supply Management*, *26*(1), 100596. http://doi.org/10.1016/j.pursup.2019.100596.

Li, X. (2020). Reducing channel costs by investing in smart supply chain technologies. *Transportation Research Part E, Logistics and Transportation Review*, *137*, 101927. http://doi.org/10.1016/j.tre.2020.101927.

Lindner, M., Bank, L., Schilp, J., & Weigold, M. (2023). Digital twins in manufacturing: a RAMI 4.0 compliant concept. *Sci*, *5*(4), 40. http://doi.org/10.3390/sci5040040.

Lins, T., & Oliveira, R. A. R. (2020). Cyber-physical production systems retrofitting in context of industry 4.0. *Computers & Industrial Engineering*, *139*, 106193. http://doi.org/10.1016/j.cie.2019.106193.

López, A., Casquero, O., Estévez, E., Armentia, A., Orive, D., & Marcos, M. (2023). An industrial agent-based customizable platform for I4. 0 manufacturing systems. *Computers in Industry*, *146*, 103859. http://doi.org/10.1016/j.compind.2023.103859.

Luzzini, D., Amann, M., Caniato, F., Essig, M., & Ronchi, S. (2015). The path of innovation: purchasing and supplier involvement into new product development. *Industrial Marketing Management*, *47*, 109-120. http://doi.org/10.1016/j.indmarman.2015.02.034.

Manavalan, E., & Jayakrishna, K. (2019). A review of Internet of Things (IoT) embedded sustainable supply chain for industry 4.0 requirements. *Computers & Industrial Engineering*, *127*, 925-953. http://doi.org/10.1016/j.cie.2018.11.030.

Mishra, R., Singh, R. K., & Gunasekaran, A. (2023). Adoption of industry 4.0 technologies for decarbonisation in the steel industry: self-assessment framework with case illustration. *Annals of Operations Research*, 1-40. http://doi.org/10.1007/s10479-023-05440-0.

Monczka, R. M., Handfield, R. B., Giunipero, L. C., & Patterson, J. L. (2015). *Purchasing and supply chain management* (6th ed.). Independence, KY: Cengage Learning.

Murugaiyan, P., & Ramasamy, P. (2021). Analyzing interrelated enablers of industry 4.0 for implementation in present industrial scenario. *Management Research Review*, *44*(9), 1241-1262. http://doi.org/10.1108/MRR-08-2020-0499.

Nakagawa, E. Y., Antonino, P. O., Schnicke, F., Capilla, R., Kuhn, T., & Liggesmeyer, P. (2021). Industry 4.0 reference architectures: state of the art and future trends. *Computers & Industrial Engineering*, *156*, 107241. http://doi.org/10.1016/j.cie.2021.107241.

Nasiri, M., Ukko, J., Saunila, M., & Rantala, T. (2020). Managing the digital supply chain: the role of smart technologies. *Technovation*, *96*, 102121. http://doi.org/10.1016/j.technovation.2020.102121.

Ocheri, C., Ajani, O. O., Daniel, A., & Agbo, N. (2017). The steel industry: a stimulus to national development. *Journal of Powder Metallurgy & Mining*, *6*(1), 156. http://doi.org/10.4172/2168-9806.1000156.

Pavin, R. D. P., & Klein, A. Z. (2015). Organizational consequences of the adoption of mobile erp systems: case studies in Brazil. *Journal of Information Systems and Technology Management*, *12*(2), 219-232. http://doi.org/10.4301/S1807-17752015000200002.

Pedone, G., & Mezgár, I. (2018). Model similarity evidence and interoperability affinity in cloud-ready Industry 4.0 technologies. *Computers in Industry*, *100*, 278-286. http://doi.org/10.1016/j.compind.2018.05.003.

Pereira, C. R., Silva, A. L., Tate, W. L., & Christopher, M. (2020). Purchasing and supply management (PSM) contribution to supply-side resilience. *International Journal of Production Economics*, *228*, 107740. http://doi.org/10.1016/j.ijpe.2020.107740.

Resman, M., Pipan, M., Šimic, M., & Herakovi□, N. (2019). A new architecture model for smart manufacturing: a performance analysis and comparison with the RAMI 4.0 reference model. *Advances in Production Engineering & Management*, *14*(2), 153-165. http://doi.org/10.14743/apem2019.2.318.

Riedmann, S., Binder, C., & Neureiter, C. (2024, February). Incorporating design principles in Industry 4.0 system architecture using reference architectures. In *Proceedings of the 4th IFSA Winter Conference on Automation, Robotics & Communications for Industry 4.0/5.0 (ARCI'2024)* (pp. 295-300). Brussels: International Frequency Sensor Association.

Sá, B. C., Souza, E. H. D., Reis, L. P., & Souza Dutra, M. D. (2022). Supply chain network design: a case study of the regional facilities analysis for a 3D printing company. *International Journal of Production Management and Engineering*, *10*(2), 211-223. http://doi.org/10.4995/ijpme.2022.17620.

Sage, A. P., & Rouse, W. B. (Ed.). (2014). *Handbook of systems engineering and management* (2nd ed.). Hoboken: John Wiley & Sons.

Saucedo-Martínez, J. A., Pérez-Lara, M., Marmolejo-Saucedo, J. A., Salais-Fierro, T. E., & Vasant, P. (2018). Industry 4.0 framework for management and operations: a review. *Journal of Ambient Intelligence and Humanized Computing*, *9*(3), 789-801. http://doi.org/10.1007/s12652-017-0533-1.

Schiele, H. (2007). Supply-management maturity, cost savings and purchasing absorptive capacity: testing the procurement–performance link. *Journal of Purchasing and Supply Management*, *13*(4), 274-293. http://doi.org/10.1016/j.pursup.2007.10.002.

Schiele, H. (2010). Early supplier integration: the dual role of purchasing in new product development. *Research Management*, *40*(2), 138-153.

Schoenherr, T., & Speier-Pero, C. (2015). Data science, predictive analytics, and big data in supply chain management: current state and future potential. *Journal of Business Logistics*, *36*(1), 120-132. http://doi.org/10.1111/jbl.12082.

Schütz, K., Kässer, M., Blome, C., & Foerstl, K. (2020). How to achieve cost savings and strategic performance in purchasing simultaneously: a knowledge-based view. *Journal of Purchasing and Supply Management*, *26*(2), 100534. http://doi.org/10.1016/j.pursup.2019.04.002.

Shabur, M. A., Rahman, K. A., & Siddiki, M. R. (2023). Evaluating the difficulties and potential responses to implement Industry 4.0 in Bangladesh's steel sector. *Journal of Engineering and Applied Sciences*, *70*(1), 158.

Shaharudin, M. R., Iranmanesh, M., Zailani, S., Tan, K. C., & Ghobakhloo, M. (2023). The impact of supply chain integration on reverse supply chain adoption. *Kybernetes*, *52*(11), 5730-5751. http://doi.org/10.1108/K-01-2022-0033.

Steiber, A., & Alänge, S. (2016). The world is changing. In A. Steiber & S. Alänge (Eds.), *The silicon valley model* (pp. 1-17). Cham: Springer. http://doi.org/10.1007/978-3-319-24921-6_1.

Stek, K., & Schiele, H. (2021). How to train supply managers-necessary and sufficient purchasing skills leading to success. *Journal of Purchasing and Supply Management*, *27*(4), 100700. http://doi.org/10.1016/j.pursup.2021.100700.

Tjahjono, B., Esplugues, C., Ares, E., & Pelaez, G. (2017). What does industry 4.0 mean to supply chain? *Procedia Manufacturing*, *13*, 1175-1182. http://doi.org/10.1016/j.promfg.2017.09.191.

Topan, E., Eruguz, A. S., Ma, W., van der Heijden, M. C., & Dekker, R. (2020). A review of operational spare parts service logistics in service control towers. *European Journal of Operational Research*, *282*(2), 401-414. http://doi.org/10.1016/j.ejor.2019.03.026.

van Weele, A. J. (2009). *Purchasing and supply chain management: analysis, planning and practice.* London: Thomson.

van Weele, A. J., & van Raaij, E. M. (2014). The future of purchasing and supply management research: about relevance and rigor. *The Journal of Supply Chain Management*, *50*(1), 56-72. http://doi.org/10.1111/jscm.12042.

Veiga, J. T., Pessoa, M. A., Junqueira, F., Miyagi, P. E., & Santos Filho, D. J. (2021). A systematic modelling procedure to design agent-oriented control to coalition of capabilities-in the context of I4. 0 as Virtual Assets (AAS). *Computers*, *10*(12), 161. http://doi.org/10.3390/computers10120161.

Voss, C., Tsikriktsis, N., & Frohlich, M. (2002). Case research in operations management. *International Journal of Operations & Production Management*, *22*(2), 195-219. http://doi.org/10.1108/01443570210414329.

Wang, H., Chen, S., & Xie, Y. (2010). An RFID-based digital warehouse management system in the tobacco industry: a case study. *International Journal of Production Research*, *48*(9), 2513-2548. http://doi.org/10.1080/00207540903564918.

Wright, C. Y., & Wernecke, B. (2020). Using Microsoft© Power BI© to visualise Rustenburg Local Municipality's air quality data. *Clean Air Journal*, *30*(1), 1-5. http://doi.org/10.17159/caj/2020/30/1.7512.

Wynstra, F., Suurmond, R., & Nullmeier, F. (2019). Purchasing and supply management as a multidisciplinary research field: unity in diversity? *Journal of Purchasing and Supply Management*, *25*(5), 100578. http://doi.org/10.1016/j.pursup.2019.100578.

Xiong, G., & Helo, P. (2008). Challenges to the supply chain in the steel industry. *International Journal of Logistics Economics and Globalisation*, *1*(2), 160-175. http://doi.org/10.1504/IJLEG.2008.020529.

Yli-Ojanpera, M., Sierla, S., Papakonstantinou, N., & Vyatkin, V. (2019). Adapting an agile manufacturing concept to the reference architecture model industry 4.0: a survey and case study. *Journal of Industrial Information Integration*, *15*, 147-160. http://doi.org/10.1016/j.jii.2018.12.002.

Zhang, G. Q., Xue, J., & Lai, K. K. (2000). A genetic algorithm based heuristic for adjacent paper-reel layout problem. *International Journal of Production Research*, *38*(14), 3343-3356. http://doi.org/10.1080/002075400418289.

Zheng, P., Wang, H., Sang, Z., Zhong, R. Y., Liu, Y., Liu, C., Mubarok, K., Yu, S., & Xu, X. (2018). Smart manufacturing systems for Industry 4.0: conceptual framework, scenarios, and future perspectives. *Frontiers of Mechanical Engineering*, *13*(2), 137-150. http://doi.org/10.1007/s11465-018-0499-5.

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