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When technologies become Industry 4.0 platforms: Defining the role of digital technologies through a boundary-spanning perspective

Guilherme Brittes Benitez[a,b], Antonio Ghezzi[c], Alejandro G. Frank[a,*]

[a] Organizational Engineering Group (Núcleo de Engenharia Organizacional – NEO), Department of Industrial Engineering, Universidade Federal do Rio Grande do Sul, Brazil

[b] Industrial and Systems Engineering Graduate Program, Polytechnic School, Pontifical Catholic University of Parana (PUCPR), Brazil

[c] Department of Management, Economics, and Industrial Engineering, Politecnico di Milano, Italy

A R T I C L E I N F O

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A B S T R A C T

The implementation of Industry 4.0 is usually built around core technologies that integrate different complementary hardware and software to coordinate activities within and across the company's borders. These technologies can operate as platforms, becoming the base of technology integration in the digital transformation journey. However, the specialized literature has not yet addressed Industry 4.0 technologies from a system view by considering the types of platforms involved. Rather, most Industry 4.0 technologies are considered singular entities of digital transformation. Thus, we aim to define which and how Industry 4.0 technologies can operate as platforms. We propose four types of platforms that support Industry 4.0 features: (i) Networked Manufacturing Operations platforms; (ii) Vertical Integration platforms; (iii) End-to-End Engineering platforms; (vi) Horizontal Integration platforms. We adopt a Boundary-Spanning (BS) perspective to analyze technologies as Industry 4.0 platforms using four BS activities: information collection and processing, external representation; task coordination; and knowledge transformation. We employ a multiple-case approach by scrutinizing 40 cases and selecting seven in which Industry 4.0 technologies are used as platforms. Although only the internet of things and cloud-based systems are conceived as technology platforms in practice, we show that Industry 4.0 can embrace other technologies as platforms that contribute to building cyber-physical systems. We suggest that some of these technologies can operate either as stand-alone or platforms, depending on how their use is designed in the digital transformation process for Industry 4.0 implementation. We provide a framework explaining platform layering as a value chain for these technologies.

1. Introduction

The Industry 4.0 concept has been built around key features. First, networked manufacturing systems and vertical integration of systems are two features deeply interconnected. They consider the interoperability of equipment and communication of operational and managerial information systems (Dalenogare et al., 2018; Tabim et al., 2021). The implementation of these features aims to obtain a flexible and reconfigurable manufacturing production system (CPS) (Enrique et al., 2022a, 2022b). Third, end-to-end engineering focuses on integrating different functional activities of the company's product lifecycle (Sony, 2018). A fourth feature is 'horizontal integration', which aims to better synchronize the company's value network, including suppliers, complementors, and other external actors (Benitez et al., 2022; Sun et al., 2020). These key features highlight the build of real-time integration and interoperability across physical and digital technologies to create cyber-physical systems. Such systems are composed of base and front-end technologies representing the scope of Industry 4.0. Base technologies like the Internet of Things (IoT), cloud computing, big data, and advanced analytics such as artificial intelligence (AI) provide the ground for digital operations (Meindl et al., 2021; Frank et al., 2019). They support other front-end or applied technologies like 3D printing, virtualization, simulation, and advanced robotics (Meindl et al., 2021; Frank et al., 2019). In this view, Industry 4.0 considers a broad set of new technologies (software and hardware) operating into integrated systems and a rule of principles with processes and goals to achieve an

* Corresponding author. Av. Osvaldo Aranha 99 - Sala LOPP 508 - 5° andar, Escola de Engenharia, Universidade Federal do Rio Grande do Sul, Centro, CEP 90035190, Porto Alegre, RS, Brazil.
E-mail address: ag.frank@ufrgs.br (A.G. Frank).

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interconnected enterprise technology model (Dalenogare et al., 2019).

The integration of different technologies to achieve the Industry 4.0 key features requires coordination technologies to provide interoperability (Tabim et al., 2021). They act as the 'brain' that synchronizes different parts of the 'body'. Such technologies are generically named technology platforms. Platforms are defined as "technologies developed by one or more firms, and which serve as foundations upon which a larger number of firms can build further complementary innovations and potentially generate network effects" (Gawer and Cusumano, 2014). Although this concept focuses on different complementary 'firms', it is also useful to consider other complementary technologies developed by these firms. In this sense, Industry 4.0 platforms should serve as the foundation to create a system of complementary technologies that are integrated to achieve operational goals and which can create network effects, i.e., a greater value when more technologies are combined and used upon them (Benitez et al., 2020; Sturgeon, 2021). Platforms should be a keystone of the digital transformation journey because they provide the ground for cyber-physical systems (Dalenogare et al., 2022). Also, some platforms can help organize a whole ecosystem of companies working together around operational standards (Benitez et al., 2020).

The Industry 4.0 community has widely acknowledged the relevance of platforms. From a practical perspective, the market has offered IoT/cloud-based platforms such as GE Predix and Siemens MindSphere. They are proposed as general-purpose technology platforms because they integrate a high variety of devices and systems from the production environment (Sturgeon, 2021; Bowen et al., 2017). Also, recent research has highlighted the importance of platforms in creating Industry 4.0 business ecosystems among different complementary technology providers (Benitez et al., 2020, 2022). However, platforms oriented to inter-organizational activities differ from GE Predix or Siemens MindSphere solutions since they aim to connect different services to develop new business models among a pool of networked companies (Rietveld and Schilling, 2021; Siqin et al., 2022). Consequently, the platform concept can vary depending on the operational and organizational aim pursued. Moreover, the complexity of defining platforms in Industry 4.0 increases when considering the cyber-physical systems created in the manufacturing environment. For instance, a real-time flexible and reconfigurable manufacturing system may depend on a broad set of technologies, including sensors, actuators, supervisory systems, and manufacturing executing systems (MES), which may also be integrated with advanced robots and/or 3D printers (Enrique et al., 2022a, 2022b; Dalenogare et al., 2018). In such a case, as reported by Benitez et al. (2020), some of these technologies can become the orchestrator of the whole system, allowing them to operate in a synchronized way with other 'add-ons' solutions. Therefore, defining an Industry 4.0 platform becomes more complex because stand-alone technologies can also operate as a foundation upon which a larger number of technologies can work, creating a system of complementary activities that generate network effects (Gawer and Cusumano, 2014).

Recent studies like Sturgeon (2021) and Siqin et al. (2022) addressed the existence of different technology platforms in the Industry 4.0 domain. Sturgeon (2021) has addressed the value chain perspective existing in diverse platforms and highlighted global standards used across industries. Siqin et al. (2022) considered the contribution of the main digital technologies like IoT, cloud and AI to different operational objectives of them as platforms. However, the current literature is mainly focused on the external operations of such platforms. Yet, little is known about conventional Industry 4.0 technologies that can also operate in some circumstances as internal platforms to create cyber-physical systems in the manufacturing environments. In this sense, Benitez et al. (2020) call for more research to understand how better articulate different production technologies around core technologies that work as platforms. As argued by these authors, identifying these core technologies can help the digital transformation process because the company will be better oriented toward central technologies that can become the orchestrators of the manufacturing cyber-physical system (Benitez et al., 2020). Furthermore, Tabim et al. (2021) recently showed that this understanding is essential when companies want to create a vertical integration of systems built around core technologies that will become the 'entrance door' to the entire digital transformation process. Such studies argue that the Industry 4.0 implementation journey should be *platform-oriented* rather than *technology implementation-oriented*. Otherwise, Industry 4.0 can become simply a use of several stand-alone digital technologies without creating an integrated cyber-physical system that comprises different manufacturing activities. In this sense, these platforms need to be related to the Industry 4.0 key features in order to better define which technologies can support such features operating as platforms in the cyber-physical systems. Also, the platform concept evolved and became more diffused, calling for more conceptual clarity and a better definition of scopes in different architectural levels in which they can be used (De Reuver et al., 2018). Therefore, we propose the following research questions: When and how can Industry 4.0 technologies operate as platforms to meet the Industry 4.0 key features?

This study analyzes Industry 4.0 technologies that can operate as platforms to support the Industry 4.0 key features. We follow Gawer and Cusumano's (2014) definition of platforms as a foundation for integrating other technologies upon it which creates network effects. We also adopt the perspective of platform layering as a value chain in the digital economy by considering different layers in which platforms can play a role in supporting Industry 4.0 features (Sturgeon, 2021). Using these theoretical concepts on platforms, we propose four types of platforms for the Industry 4.0 context: (i) Networked Manufacturing Operations platforms; (ii) Vertical Integration platforms; (iii) End-to-End engineering platforms; and (iv) Horizontal integration platforms. Following these types of platforms that meet Industry 4.0 features, we use the boundary-spanning theory as an analytical reference to define the degree to which a specific technology connects with its surroundings and operates as a platform (Aldrich and Herker, 1977). From this theory, we consider four main activities of the technologies (Aldrich and Herker, 1977; Ancona and Caldwell, 1992; Tippmann et al., 2017): information collection and processing; external representation; task coordination; and knowledge transformation. We then analyze how all these defined platforms for Industry 4.0 characterizes the three main perspectives on platforms (engineering, organizational, and economic) by considering key elements and their differences across such platforms, namely: peripherical architecture, contributors and complementors, specialization and complementarity, and network effects and switching costs. We employ a multiple-case approach by scrutinizing 40 cases and selecting seven of them in which Industry 4.0 technologies are used as platforms. While only IoT platforms and cloud systems are usually known as technology platforms, our results show that Industry 4.0 can embrace other technologies as platforms for technology integration to create cyber-physical systems. This includes technologies such as 3D printer, MES, ERP, and PLM when supported by IoT and cloud systems. We show that some of these technologies can operate either as stand-alone technologies or platforms, depending on how their use is designed in the digital transformation process for Industry 4.0 implementation. As the main contribution, we provide an Industry 4.0 platform taxonomy. This helps scholars to understand technology classification as platforms through their role in four main activities (information collection and processing; external 'representation; task coordination; and knowledge transformation), and their contribution to the Industry 4.0 key features, as well as their main impacts and contributions as platforms from an engineering, organizational and economic perspective. Our study opens up a new discussion on the implementation of Industry 4.0. We argue that future research needs to develop maturity processes and implementation models built around platforms as a keystone and not based on stand-alone and interdependent technologies. Managers can find help in this study to build the company's cyber-physical systems better orchestrated through the considered platforms.

2. Theoretical background

2.1. Platforms in the Industry 4.0 context

Technology platforms have received attention from several research fields with complementary perspectives (Shree et al., 2021). Rolland et al. (2018) expanded a previous view on platforms proposed by Gawer (2014), summarizing three perspectives usually addressed in the information systems literature: *engineering*, *economic* and *organizational*. These perspectives are shown in Table 1 and explained next.

Following a chronological line, the engineering perspective was the first to be conceived. It started in the product development stream when the focus was to create innovation from a core technology that could be deployed into several solutions for the customer by adding, substituting, or removing modular components (Wheelwright and Clark, 1992). This view also evolved toward industry platforms, i.e., products, services, or technologies upon which other solutions can be developed, generally provided by third parties (Gawer, 2011). This is the case with operational systems such as Windows, iOS, or Linux that allow running different types of software on them as add-ons (Gawer and Cusumano, 2014). Thus, in a broader sense, the engineering perspective conceptualizes technology platforms as "technical artifacts with a modular architecture consisting of a stable core component and many changing peripheral components" (Rolland et al., 2018). They aim to connect other technologies and systems to manage the information flow and drive innovation in the environment, being an architecture for information exchange and integrated activity for intra- or inter-organizational ecosystems (Wang, 2021). This perspective emphasizes the supply side by focusing on how technologies operate in architectures and arrangements around the core technology (platform) (Gawer, 2014). Some functional elements are necessary to define such architectures (Bonina et al., 2021). First, a core architecture contains core modules from which complements can be built. The core architecture is also developed with contributors that participate in the core architecture. Then, the platform also needs a peripheral architecture, like interfaces, to enable the complementors to contribute to the ecosystem through solutions as add-ons. Thus, platforms will have a permanent and context-dependent (peripherical) part (Bonina et al., 2021).

The economic perspective, on the other hand, defines platforms as disruptive markets that facilitate efficient interactions between consumers and producers (Rolland et al., 2018). This perspective characterizes an environment created by digital technologies (e.g., online marketplaces) where transactions are mediated between two (two-sided markets) or more groups of agents (multi-sided markets) (Shree et al., 2021; Parker and Van Alstyne, 2005). These platforms provide goods or services to several distinct groups of customers (i.e., B2C – business-to-consumer markets), all of whom need each other in some way and rely on the platform to mediate their transactions (Shree et al., 2021; Amit and Zott, 2001). Consequently, the economic perspective emphasizes the demand side (market) and focuses on competition among consumers and producers operating on the platform (Gawer, 2014). It is less concerned with the technology itself and more with the business models and value creation (Rolland et al., 2018). This perspective emphasizes the potential of the platform to generate network effects, i.e., to create value in their surroundings. The more this value is created, the more central and valuable they become (Gawer and Cusumano, 2014; Parker and Van Alstyne, 2005). It also stresses the role of switching costs when platforms are adopted, meaning that it will be costly for users to switch to other firms and solutions due to technology dependency (Tucker, 2019).

Finally, the organizational perspective defines platforms as "innovation practices in which actors organize and coordinate innovation enabled by technical mechanisms and social arrangements" (Rolland et al., 2018). Another definition by Lehtinen et al. (2019) considers it an organizational structure that stores multiple actors and their resource constellations (intangible and tangible) to create joint value. Thus, this perspective emphasizes the actors of the ecosystems and their interactions to create value through coopetition, i.e., cooperation and competition. According to this view, the organization enabled by technologies can operate as a platform for the ecosystem actors' activities (Ciborra, 1996). These actors have two key characteristics in organizational platforms: specialization and complementarity of resources to create value (Lehtinen et al., 2019).

In this study, we follow the engineering perspective to consider Industry 4.0 technologies that can become the core component combined with peripherical components through modularity (Rolland et al., 2018; Bonina et al., 2021). This view is concerned with the architecture, integration, and interoperability of the technologies and the platform. However, we also combine this perspective with elements of the other two perspectives described in Table 1. By discussing the architecture of the Industry 4.0 platforms, we also consider the network effects and switching costs they can create in their surroundings, as proposed by the economic perspective, and also the specialization and complementarity needed for some technologies to become Industry 4.0 platforms, as considered in the organizational perspective.

Finally, it is also important to consider the openness of the platforms with their interfaces (Gawer, 2014). Independently of the perspective adopted to the study of technology platforms, their level of analysis can be focused at the firm – as an internal platform, at the supply chain – as a middle-range platform, or at the industry level, as an ecosystem platform (Gawer, 2014). Internal platforms tend to be closed systems that can connect the company's technologies, while external platforms oriented to ecosystems can create open marketplaces in which different technologies and actors can operate (Parker and Van Alstyne, 2018; Gawer, 2014). We aim to explore all these variances by considering the different and interconnected layers of Industry 4.0 platforms, as explained in the next section.

2.2. Types of Industry 4.0 platforms

This study adopts the theoretical perspective of platform layering as a value chain in the digital economy (Sturgeon, 2021). According to this view, each layer of the value chain, from the bottom line of the production process activities to the highest hierarchical level of the corporation and inter-organizational relationships, can be supported by central technologies operating as platforms. Each layer comprises platforms that rely on a dynamic mix of modular platform complementors, creating network effects. Fig. 1 represents this view: different generic types of platforms support an ecosystem of modular solutions in their

Table 1
Different perspectives on platforms (Source: Adapted from Gawer, 2014 and Rolland et al., 2018).

Perspectives	Conceptualization	Emphasis	Focus	Key elements
Engineering	**Technical artifacts** with a modular architecture consisting of a stable core component and many changing peripheral components	Supply	Innovation	Core architecture, peripherical architecture, contributors and complementors
Economic	**Disruptive markets** that facilitate efficient interactions between consumers and producers	Demand	Competition	Network effects and switching costs
Organizational	**Innovation practices** in which actors organize and coordinate innovation enabled by technical mechanisms and social arrangements	Ecosystem's actors	Coopetition	Specialization and complementarity

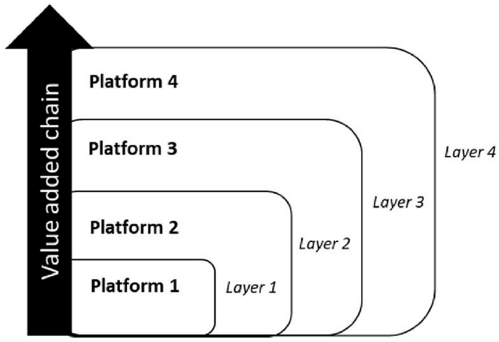

Fig. 1. Representation of Sturgeon's (2021) perspective of platform layering as a value chain.

own layer that are interconnected with the next layer, creating a value-added chain. Each layer represents a step of the value chain of the organizational processes, which can comprise the shop floor, organizational, or market activities. Other streams of research in the information systems and technology management literature have also considered that platforms can be deployed in several layers. For instance, Bonina et al. (2021) discuss the different layers of digital platforms, presenting social media, sharing economy, knowledge sharing, digital identity subcategories, and transaction and innovation macro categories. De Reuver et al. (2018) also present core concepts and divide digital platforms' general concept into multisided platforms, multisided markets, direct network externalities, indirect network externalities, technical view, and sociotechnical view, among others. Gawer (2014), one of the main contributors in platform studies, presents three platform layers – internal, supply chain, and industry – which vary from close to open and managerial authority to ecosystem governance, respectively. Such layers are highly adopted and discussed in information systems literature (e.g., Chew, 2016; Rolland et al., 2018; Foerderer, 2020).

We adapted this view of platform layering as a value chain to the context of Industry 4.0. The first report of the German government that conceptualized Industry 4.0 proposed key features that are pursued with the use of digital technologies and that can be conceived as layers of the platform value chain (Kagermann et al., 2013): (i) networked manufacturing operations, (ii) vertical integration of systems, (iii) end to end engineering, and (iv) horizontal integration across the value chain. These key features vary from the shop floor operations to the integration of external actors, respectively, and are supported by a set of digital technologies (Kagermann et al., 2013). We use these features as value chain layers supported by specific platforms that can be connected with other modular complementors to create network effects and provide higher value to the system, as explained below.

The first layer is represented by '*networked* manufacturing operations platforms'. It comprises any core technology in the factory (shop floor) able to orchestrate the smart production system (Weking et al., 2020; Zhong et al., 2017). This type of platform is part of the operational requirements for Machine-to-Machine (M2M) communication, which considers the synchronization between different machines and equipment (Jeschke et al., 2017; Dalenogare et al., 2018). This feature of the Industry 4.0 concept considers mainly hardware technologies that will operate with real-time synchronization to execute the production process. Also, information technologies used on the shop floor to coordinate these internal activities can be part of this feature when they enable different machines to work in synchronization (Kagermann et al., 2013). Companies can have such a type of technology connected through IoT with other processing technologies and systems, becoming the central piece of the factory (Sun et al., 2020; Benitez et al., 2020; Dalenogare et al., 2018).

The second platform layer of Industry 4.0 requires vertical integration platforms. These platforms manage and integrate real-time data from different stages of the organizational hierarchy through information systems (De Reuver et al., 2018). Tabim et al. (2021) discuss the need for such platforms as one of the first steps of the Industry 4.0 journey to create internal visibility and transparency of production activities. As pointed out by these authors, these platforms need to be flexible and capable of communicating with several interphases and technologies to be able to create a common virtual field of information and data sharing that integrate long-term demand planning with the real production capacity and operational conditions (Bueno et al., 2020). The German report on Industry 4.0 implementation presents this key feature of Industry 4.0 in a single bundle with the first feature of networked manufacturing operations (Kagermann et al., 2013). While networked manufacturing focuses mainly on integrating hardware and devices, this latter emphasizes the informational flow for decision-making. Both are necessary to create a smart manufacturing environment (Frank et al., 2019).

Third, platforms should also contribute to the integration and interoperability of technologies along the functional activities of the company, connecting, for instance, engineering and manufacturing activities (Dalenogare et al., 2018). We call this third layer 'End-to-end Engineering Platforms', following the same name as this key feature of Industry 4.0 (Kagermann et al., 2013). At this layer, technologies operating as platforms should ensure that data and information flow across different functional activities of the company, such as production engineering and manufacturing, to provide visibility and transparency of the business processes that connect the manufacturing activities with other functions of the enterprise (Kagermann et al., 2013). Such technologies should work as orchestrators of several existing databases and technologies from the functional areas to create a unique view of the company.

Finally, the most external (intra-organizational) type of industry platform considers technologies oriented to the integration with external partners. This platform is usually considered in the business and innovation ecosystem literature (Wang, 2021; Foerderer, 2020). In the Industry 4.0 context, we call them Horizontal Integration Platforms because they integrate the external value chain, as preconized by one of the Industry 4.0 features (Kagermann et al., 2013). In this intra-organizational context, platforms should provide interoperability and integration among the technologies and solutions used between the company's stakeholders, including suppliers, distributors, and customers (Benitez et al., 2022; Dalenogare et al., 2022).

2.3. Boundary-spanning theory in Industry 4.0 platforms

Following our conceptualization of platforms in the Industry 4.0 context and the possible generic types proposed (Section 2.2), we aim to use a theoretical perspective that allows us to define specific technologies that can be seen as such types of platforms, using an engineering perspective (as discussed in Section 2.1). To this aim, we adopt the boundary-spanning (BS) theory. This theory explains coordination and communication activities across entities in a network by creating linkages within and across boundaries (Aldrich and Herker, 1977; Piercy, 2009). BS has been studied from an array of views, especially in network analysis and business ecosystems, from a social perspective on BS individuals in organizations (Cano-Kollmann et al., 2016; Tan et al., 2020). On the other hand, the information systems literature has also considered information systems and technologies as potential BS objects that connect and communicate with their surroundings and build a communication network (Gasson, 2006; Yao et al., 2009), which is in line with the engineering perspective of platforms as technical artifacts with a modular architecture consisting of a stable core component and many changing peripheral components (Gawer, 2014). According to this theory, BS objects are artifacts (technologies) through which inter-organizational relationships are coordinated to acquire knowledge, develop new products, and foster innovation (Levina and Vaast, 2005). In this same vein, we argue that the BS theory can support the conceptualization of technologies that work as platforms in the Industry

4.0 context. We propose that using platforms as boundary-spanning objects will stimulate the creation of innovative and complex technology systems (i.e., cyber-physical systems) inside firms and business opportunities by integrating the external environment.

From an analytical perspective, BS theory proposes different activities of the boundary object that can be used to assess whether an Industry 4.0 technology can be a platform (i.e., a boundary object). In this sense, BS activities allow measuring the degree of connection that certain technology has with its surroundings. The original proposal from Aldrich and Herker (1977) encompasses two main BS activities: *information collection and processing* and *external representation*. *Information collection and processing* is the selection, transmission, and interpretation of information around the object. This activity helps define how technologies, when connected, allow for interoperability in processes. *External representation* reflects actions that persuade other entities by creating favorable impressions about the product or organization to obtain resources, high commitment, and financial support. From a technology perspective, external representation refers to the value created by the central object that justifies being interrelated. Thus, external representation activity can clarify how to foster collaboration and consequently shape businesses through platforms. Alongside the expansion of the theme in literature, two other activities have been suggested as paramount for innovation: *task coordination* and *knowledge transformation*. *Task coordination* was first introduced in organizational studies by Ancona and Caldwell (1992) to account for the facilitation of effective decision-making and intergroup dependencies. This activity can explain how technologies are integrated to work organically to develop more complex solutions. *Knowledge transformation* was introduced in management studies as the activity that transforms knowledge across organizations' boundaries into new opportunities for innovative and creative outcomes (Schotter et al., 2017; Tippmann et al., 2017). This activity can help understand how platforms based on Industry 4.0 technologies can manage information to develop complementary innovations.

We show in Fig. 2 how we aim to use these four BS activities. We propose to analyze four types of Industry 4.0 generic platforms using a platform layering as a value chain view (Section 2.2). The first type, *Networked Manufacturing Operations Platforms*, considers the most operational activities, in which platforms must integrate different manufacturing technology. Fig. 2 shows that this type of platform can connect with the second type, *Vertical Integration Platforms*, which aims to support the integration of different informational layers and systems of the organizational hierarchies. They can also help a third type of platform, *End-to-End Engineering Platforms*, which support the integration of inter-functional technologies and systems to provide information and data flow across the company's activities. Then, the final type of platform is the *Horizontal Integration Platforms* which should allow the interoperability of different inter-organizational technologies in the company's value chain. Our theoretical perspective considers BS a reference structure to define when and how Industry 4.0 technologies meet platform requirements. In this sense, we first consider the technical activities of BS (information collection and processing and task coordination), which are basic capabilities that all platforms need to cover. Moreover, our BS perspective also considers the organizational activities of BS (external representation and knowledge transformation). These are characteristics mainly present in general-purpose platforms. Such platforms are those that call for the integration and collaboration not only between operational technologies but also between different business partners who can develop solutions and find value in the collaboration through the platform integration. We use this structure of analysis to analyze several Industry 4.0 technologies and understand whether they operate as platforms. Finally, after defining the technologies that can act as a platform at each value chain layer through the BS elements, we analyze the platform's main characteristics of the identified technologies, as described in Section 2.1. Such characteristics help to understand the platform profile and the effects they produce in the ecosystem.

3. Research method

We adopted an empirical case study research approach based on qualitative data collection and analysis (Barratt et al., 2011). We chose this research approach because it is useful to deeply investigate complex phenomena to generate novel insights (Barratt et al., 2011; Goffin et al.,

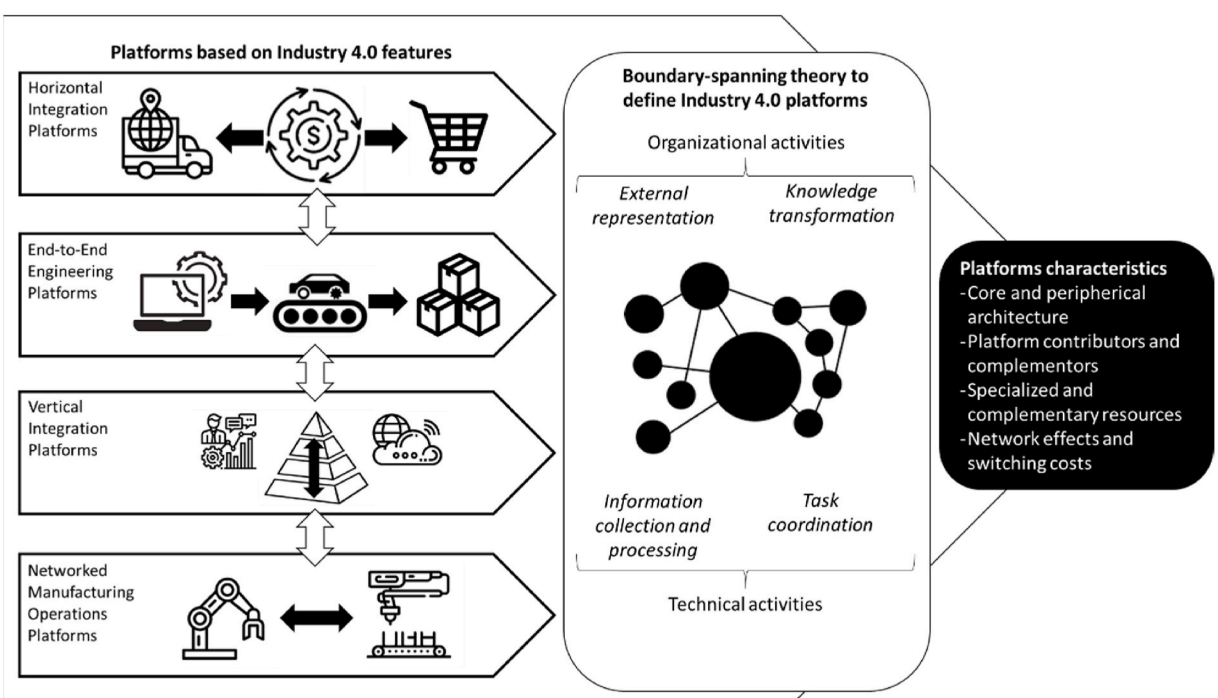

Fig. 2. Conceptual representation of the boundary-spanning perspective on Industry 4.0 platforms.

2019). We selected a multiple-case approach rather than a single-case analysis to augment external validity and reduce potential observer bias (Voss et al., 2002). We employed the conceptual representation of Fig. 2 to guide our empirical study. This figure summarizes the types of Industry 4.0 platforms pursued and the BS activities considered to conceptualize a technology as platform. Our research design followed the guidelines of Voss et al. (2002) for case study research, as described in the following subsections.

3.1. Industry 4.0 technologies analysis

Our initial step was an in-depth analysis of Industry 4.0-related technologies to conceive which technologies could be evaluated in our study in the operations management field (Anand and Gray, 2017). As a result, Table 2 presents 17 technologies related to Industry 4.0. We leveraged previous works from Dalenogare et al. (2018), Frank et al. (2019), Culot et al. (2020), Marcon et al. (2022), and Enrique et al. (2022a, 2022b), as a guideline to select such technologies. Such works allowed us to consider also a progressive view on Industry 4.0 technologies since they evolve quickly due to their emergent nature. Following such studies, and because we aim to define different types of platforms, we consider both software and hardware as technologies that are potentially able to work as platforms. Software and hardware have been considered key enabling technologies of Industry 4.0 that can contribute to different operational functions of a cyber-physical system (Culot et al., 2020). Also, some works have considered that Industry 4.0 only comprises disruptive technologies, especially those based on Artificial Intelligence (AI) and the Internet of Things (IoT) (Almada-Lobo, 2016; Sturgeon, 2021). In contrast, other studies followed in our research have integrated classical advanced manufacturing technologies, including robotics and automated machines, which can be boosted by IoT and AI (Frank et al., 2019; Osterrieder et al., 2020). Moreover, although some information systems such as ERP, MES, and SCADA have existed in industrial automation since the 3rd Industrial Revolution, they have been considered in the Industry 4.0 context as key enablers of vertical and horizontal integration (Jeschke et al., 2017; Gilchrist, 2016). We also considered them as potential technologies for our analysis because some authors like Frank et al. (2019) and Tabim et al. (2021) explain these systems work as information technologies that support the informational architecture of cyber-physical systems in the Industry 4.0 context. Finally, Dalenogare et al. (2018) considered a list of technologies that are usually seen in different industries. Similarly, Frank et al. (2019) have suggested that Industry 4.0 should be seen from a set of 'base technologies' – namely IoT, Cloud Computing, Big Data, and Analytics and Artificial Intelligence (AI) – that support 'front-end technologies' like robotics, information systems, and smart machines. In Table 2, we summarize the technologies frequently associated with the Industry 4.0 concept. In this table, we use the predefined labels adopted in prior research and describe technologies that represent these labels. We also provide a short definition of each technology considered, following studies on each technology.

The technologies presented in Table 2 are often considered enablers of the connectivity and integration processes in IIoT (Industrial Internet of Things) (Gilchrist, 2016; Jeschke et al., 2017). We analyzed these 17 technologies in a multiple-case study to comprehend which of them can be classified as platforms (and how) in the Industry 4.0 context. We selected companies that offer or have adopted at least one of these technologies. All technologies presented in Table 2 are related to one of these companies. Next, we describe the case study selection procedures.

3.2. Case study selection

For the case study selection, we first selected a national context to help delimitate the scope of selected cases. In this sense, we focused on companies operating in Brazil based on our access to industry associations that allow for preserving a neutral selection of leading companies

Table 2
Industry 4.0-related technologies.

Categories	Technologies	Definition
Vertical Integration (Tabim et al., 2021; Enrique et al., 2022a, 2022b)	Enterprise Resource Planning (ERP)	Technologies that can integrate all data and processes needed to manage a company (Gilchrist, 2016).
	Manufacturing Execution System (MES)	Technologies that work in real-time to enable the control of multiple elements of the production process (Almada-Lobo, 2016; Jeschke et al., 2017; Tabim et al., 2021).
	Supervisory Control and Data Acquisition (SCADA)	Technologies for monitoring shop floor operations through real-time data collection (Jeschke et al., 2017).
Base technologies (Frank et al., 2019)	Internet of Things (IoT)	Technologies of interrelated computing devices and physical devices that are connected to the internet with the ability to transfer data over a network without requiring human-to-human or human-to-computer interaction (Fahmideh and Zowghi, 2020; Frank et al., 2019).
	Cloud computing	Computing activity that relies on distributed resources rather than having local servers or personal devices to handle applications (Frank et al., 2019)
	Big data	A large amount of data accumulated to be analyzed computationally to reveal patterns, trends, and associations, especially relating to human behavior and interactions (Frank et al., 2019).
	Analytics and Artificial Intelligence (AI)	Analytics is the capacity for analyzing data with advanced techniques such as artificial intelligence. Artificial intelligence is a wide-ranging branch of computer science concerned with building smart machines capable of performing tasks that typically require human intelligence (Frank et al., 2019; Sturgeon, 2021).
Virtualization (Dalenogare et al., 2018; Frank et al., 2019)	Virtual commissioning	Debug real data of the equipment in a virtual environment, simulating the automation equipment virtually, validating its operation in the production line (Da Costa et al., 2019; Jeschke et al., 2017).
	Digital manufacturing	Use of data management systems with data management technologies and simulation technologies for manufacturing optimization before starting production, supporting the ramp-up phases (Aversa et al., 2021).
	Machine vision	Detection of the positioning of objects by image processing systems for quality control (Tao et al., 2018).
	Augmented and virtual reality	Real-scene integration with computer-generated

(continued on next page)

Table 2 (*continued*)

Categories	Technologies	Definition
		information. Integration of the real with the virtual world (Frank et al., 2019; Jeschke et al., 2017).
	Edge computing	Cloud computing systems that perform data processing at the edge of the network, near the source of the data, thus avoiding latency (Stephanie et al., 2021).
	Smart grids	Electricity network systems to optimize energy efficiency with the exchange of real-time information with the existing power grid (Park et al., 2014).
Physical process (Culot et al., 2020)	3D printing (additive manufacturing)	Versatile manufacturing machines for flexible manufacturing systems (FMS), transforming digital 3D models into physical products (Friesike et al., 2019; Weller et al., 2015).
	Collaborative robots	Robot systems with sensors and processors, enabling direct cooperation with human operators (Bartodziej, 2016; Gilchrist, 2016).
	Industrial robots	Processes automated by internal robotic mechanisms, without human intervention (Gilchrist, 2016; Tao et al., 2018).
	Flexible lines	Self-organized systems (production lines) that can be dynamically reconfigured to adapt to different product types where massive information is collected and processed to make the production process transparent (Wang et al., 2016a, 2016b, 2016a, 2016b; 2016a, 2016b).

that represent the concepts pursued in our study. Brazil has a Chamber of Industry 4.0 organized by the Ministry of Science and Technology, which congregates strong industry associations focused on the advanced of Industry 4.0 implementation like the Brazilian Federation of Industries (CNI), the Brazilian Associations of Machinery and Equipment Builders (ABIMAQ) and the Brazilian Association of the Electro-electronics Industry (ABINEE). This allowed us to access a strong pool of companies to select our best cases. Also, there is a vast literature in leading journals showing Industry 4.0 applications in this country, as signal of the existence of strong representativeness of the investigated issue (e.g., Dalenogare et al., 2018; Frank et al., 2019; Kahle et al., 2020; Benitez et al., 2020; ; 2022a, 2022b; Bianco et al., 2022). However, the country's location was not the determinant factor in choosing the cases – it was only used to design a scope of the company's selection: from the seven companies investigated (see Table 3), only two were nationals, and the other five are multinationals operating in this country.

The cases were selected based on their market recognition in the Industry 4.0 field and technology portfolio. Such recognition is given by the members of the Chamber to leading companies in the Industry 4.0 field in the country. On the other hand, for technology adopters, we selected companies engaged with these seven technology providers, i.e., companies who adopted one or more Industry 4.0 technologies from these providers. These technology adopters have what are considered advanced factories in the industrial benchmarking of the Brazilian National Confederation of Industries and are early adopters of Industry 4.0 technologies as platforms.

From a theoretical perspective, our cases were selected by means of theoretical sampling (Eisenhardt and Graebner, 2007). Cases were selected because they are relevant to shed light on the constructs under scrutiny (i.e., platforms types). As a first step, we identified and selected companies committed with the provision or adoption of Industry 4.0 technologies. We did this selection with the indication of such companies by the members of the Chamber, who provided a list of the best companies in the country. We intentionally split our sample into technology providers and technology adopters to produce contrasting results that can offer a broader picture of the phenomenon and facilitate the generalization of the results (Barratt et al., 2011; Goffin et al., 2019). This distinction was necessary to conceive how some technologies were developed to be operated by technology providers and how they are operating inside firms (i.e., technology adopters). In other words, providers deliver the technologies presented in Table 2, while adopters widely implement one or more of these technologies. The companies were chosen using the following three criteria: (i) be indicated as a leading global technology provider/adopter by the members of the Chamber; (iii) be committed with Industry 4.0 trends (according to websites, reports, and news); and (iii) be a provider/adopter of one or more Industry 4.0-related technologies (Table 2).

We screened a preliminary list of 40 potential cases (21 technology providers and 19 technology adopters) to ensure the maximum representation of the technologies under investigation. We selected only cases where Industry 4.0 technologies can be configurated as a platform, using Step 1 of our protocol of data analysis (see Appendix A). This selection also aimed to obtain theoretical saturation, i.e., when one case

Table 3
Background of the cases.

Case	Description	Size	Business Unit contacted	Classification	Data Source
A	Multinational company from the automation and control industry focused on pneumatic and electrical automation	+20,000 employees	Brazilian branch	Technology provider	Product Portfolio Manager
B	Brazilian national company from the IT industry focused on software and data processing	50-100 employees	Headquarters (HQ)	Technology provider	Development Director
C	Brazilian national company from the electronics industry focused on IoT solutions	50-100 employees	Headquarters (HQ)	Technology provider	CEO
D	Multinational company from the IT industry focused on computer, hardware, and IT services	+150,000 employees	Cloud + AI Group	Technology provider	Senior Product Manager
E	Multinational company from the automation, digitization and electrical industries	+385,000 employees	Digital Factory Division	Technology provider	Business Developer Engineer
			Software Division		Portfolio Development Executive
			Business Division		Product and Marketing Engineer
F	Multinational company from the manufacturing industry focused on auto and aerospace parts	+55,000 employees	Brazilian business unit	Technology adopter	Launch Manager Leader and Vice President of Engineering & Technology
G	Multinational company from the automotive industry focused on heavy vehicles	+50,000 employees	Brazilian business unit	Technology adopter	Executive Manager

contained sufficient evidence, we did not look for complementary cases. In contrast, in other cases, we needed to reinforce with additional cases to consolidate our understanding of the technology. This explains why in some cases of platforms, we only have one case, while in other cases, we use more than one case. Moreover, we included in our cases two medium-sized technology providers (B and C) for our final analysis. These companies were selected due to their core businesses, which are specific to providing an integrated and connected platform for their customers. We also chose two technology adopters with one Industry 4.0 platform implemented in their systems. From these two cases, we selected one which established a complete vertical integration with its ERP system as the main technology and another with a 3D printer as the leading technology in its manufacturing system. We studied and classified each of these cases into one of our four proposed platform types. In all cases, we classified the platform type by analyzing the presence of BS activities, as described in Fig. 2. Finally, each case was organized by platform type and described in our results. Table 3 provides a brief description of each case study. Companies' and respondents' names were omitted to preserve anonymity[1]

3.3. Research instruments and data collection procedures

The multiple-case study approach was based on data collected from different sources (Barratt et al., 2011). We first employed semi-structured interviews with technology providers. Afterward, we interviewed technology adopters, i.e., enterprises that adopted and implemented one or more Industry 4.0 technologies in their systems. The interviews were conducted from March 2019 to March 2020 using a semi-structured interview guideline (see Appendix B) adapted from Rong et al. (2015), Müller et al. (2018) and Benitez et al. (2020) Industry 4.0-related works. The interviews were focused on capturing cases where Industry 4.0 technologies act as platforms in the companies. In this sense, our discussions emphasized the identification of BS activities (i.e., information collection and processing, external representation, task coordination, and knowledge transformation) present in the technologies of each case. For instance, if a technology does not show some BS activity, it was discarded from our analysis as a potential platform case. Moreover, we asked the interviewees to provide arguments and examples of how their technologies work and affect their business in terms of the platform characteristics described in Section 2.1. In some cases (from our final sample, only case G), we visited technology adopters to observe how their Industry 4.0 technologies operate in their systems. We complemented our research by analyzing secondary data (reports and websites) for technology providers. Table 4 describes our secondary data collection and relation to each case from our final sample.

Table 4
Secondary data organization.

Case company	Complementary data
A	Technical visit; industrial report; video; website; and news.
B	Technical visit; industrial report; and website.
C	Technical visit; industrial report; and website.
D	Industrial reports; website; video; industrial fairs; government records; and news.
E	Industrial reports; website; social media; video; industrial fairs; government records; books; and news.
F	Website; video; industrial report; and website.
G	Technical visit; video; industrial report; and website.

Finally, for each interview, we followed a snowball approach, using the next interview to collect new data and contrast statements (in this case, compare the interviews of technology providers and technology adopters). The responses were analyzed, and, in a few cases, it was necessary to make phone calls to clarify specific statements. We performed one interview per company, totalizing 40 interviews that lasted around 1.5 h each. At least two research assistants took notes of the main comments while the main researchers conducted interviews. The interviews were also recorded and later transcribed.

3.4. Data analysis - validity, reliability, and interpretation

For construct validity, we followed Voss and colleagues' (2002) guidelines for the correct operational measures from our cases. In terms of external validity, we conducted a multiple-case study and compared evidence on a selection of different companies that had a strong involvement with Industry 4.0 technologies. Thus, we followed a research codification protocol described in Appendix A. We structured our codification protocol based on previous works by Ayala et al. (2017) and Benitez et al. (2020) for qualitative analysis. Moreover, Voss et al. (2002) recommend data triangulation and multiple sources of evidence for construct validity. Therefore, we used secondary data (e.g., industrial reports) about companies related to Industry 4.0 technologies provision and, in some cases, company websites and news. In addition, we visited some technology adopters to deepen our understanding of their Industry 4.0 applications. Finally, all procedures in our research were performed in four different stages of the study, as described in the protocol of Appendix A.

Since most of our selected cases were from technology providers, such interviews allowed us to obtain a broad view of using such technologies in practice. This is because technology providers can see several applications of the technology offered differently from technology adopters that only know the context of the application. This strategy ensured that our cases were not predominantly contextual-dependent and hard to generalize. Appendix B details the main questions made for technology providers and technology adopters. Moreover, Appendix C highlights the most important quotes from the interviewees used in our results as a source of evidence for the analysis conducted.

We built a four-step research protocol presented in Appendix B to collect and organize our data. One key point to proceed to the next step was to reach theoretical saturation during our data organization (Voss et al., 2002). To reach this in Step 1, we identified which Industry 4.0 technologies the enterprise provides/uses and the company's core business. This step was the starting point to understanding how providers sell their Industry 4.0-related technologies and how adopters apply them. We adopted this approach to ensure that both sides of the dyad are connected to achieve generalization in our results (Bowen, 2008). In Step 2, called 'Industry 4.0 technologies analysis and case study selection', we analyzed the presence of the four BS activities to classify them as technology-as-platform or not. In many cases, the companies had more than one single technology to be analyzed, so, besides this analysis, the profile scrutiny and technology applications helped us as a complementary analysis to classify each case. Finally, if the case fulfilled these requirements, we selected it for our final data compilation; if not, we excluded it from our analysis.

Because some technologies have their original purpose of managing information flow (e.g., ERP system), we emphasized our focus on these technologies. In other words, we analyzed whether, in fact, these technologies are the core technology in the firm that manages information from other technologies, systems, departments, or partners with the support of other technologies through connectivity and integration. In Step 3, called 'Data triangulation', we used multiple sources of information by including data from websites, reports, and notes from industrial visits to the companies investigated, which were combined with our transcribed interviews to analyze each technology classified as a

[1] Our cover letter to the editors provides the companies' identification and the names of the interviewees to ensure the transparency of the data collection process.

platform. We also checked the notes and observations made during the interviews to refine our findings. We verified similarities and patterns among the technologies/systems applied as platforms by analyzing BS activities by adopting a content analysis approach. This approach followed a meaning rule, which consists of identifying common issues and grouping them according to the interpretation given to their meaning and based on predefined labels (McCutcheon and Meredith, 1993).

In Step 4, we analyzed where the presence of BS activities is stronger by measuring the degree of BS activities presence and classified the platforms according to our proposed types. This step helped us to understand better how such platforms manage information flow. We classified two elements to capture the information level each platform case can reach: inside borders and outside borders. Inside borders refer to the BS activities within the firm. On the other hand, outside borders refer to the BS activities with external actors. This last step allowed us to identify the type of platform considered in each technology analyzed.

Moreover, in terms of reliability, we proceeded with independent analyses with the support of three research assistants and then discussed our insights. We used interview records and the enterprises' websites to check divergences between understandings and contacted the interviewees again for further clarification when necessary. Finally, we summarized our data analysis and case study narrative in an overall classification framework (Fig. 4). This framework helped us to consolidate our overview of how Industry 4.0 technologies operate as platforms and which kind of information flow management they can reach. The overall classification framework also allowed us to visualize how BS activities are present in each technology and on each type of platform.

4. Results

We organized our results, subdividing the sections into two main points that follow our analytical framework presented in Fig. 1: (i) Definition of the core architectures for Industry 4.0 platforms; and (ii) Consolidation of the Industry 4.0 platforms' characteristics. In the first part (i) we present a description of each case study and how the technology is defined as a platform through the BS activities; and then we consolidate the typology of technologies as Industry 4.0 platforms for the specific Industry 4.0 feature analyzed (i.e., networked manufacturing operations, vertical integration, end-to-end engineering, and horizontal integration). In the second part (ii) we use the key element from Table 1 to organize the defined Industry 4.0 platform according to the engineering, organizational and economic perspectives. All cases are classified with an additional letter in brackets in the text. In addition, we provide in Appendix C a list of quotations that support and exemplify the results presented in this section.

4.1. Definition of the core architecture for Industry 4.0 platforms

4.1.1. Networked manufacturing operations platforms

This type of platform refers to technologies that support manufacturing processes' operation and create an interface and integration among different manufacturing processing technologies. As explained next, we identified two technologies in this category working as platforms.

4.1.1.1. Using digital twin as platforms. Company A aims to provide flexible manufacturing systems based on Industry 4.0 concepts. Such flexible lines comprise a set of different manufacturing technologies, including computer numerical control (CNC) modular machines that can be dynamically reconfigured to adapt to different product types, industrial robots for processing activities, collaborative robots, automated processing systems supported and equipped with sensors, machine vision, and pneumatic systems, among other technologies according to the customer demand. These lines enable the production of different kinds of products in small batches, with minimum loss of productivity and a higher level of flexibility in processes, allowing modularization and customization in a single production line.

To provide such flexible lines, the company uses a *digital twin* as the 'core architecture' technology that operates over physical manufacturing technologies that operate as the peripherical architecture. This solution allows first to create a mirror of the production system and then simulate scenarios, define variables to organize the production system in a flexible approach, and send orders from the virtual arrangements to the physical structures of the equipment. In this sense, the digital twin provides *task coordination* because it simulates new processes, defines better production routes, and executes such functions through M2M (machine-to-machine) communication among the synchronized manufacturing machines (e.g., robots, CNCs, and automated systems). The virtualization of the different operations in the simulation tool requires information collection and processing from the various manufacturing technologies that need to be supported by IoT. The other technologies are connected and send information to the virtual model of the plant, which is a live operating system model which permits simulating and changing configurations before the real decision is made. It also helps companies to reduce setup times and model more production routes. The technology has become a central task coordination tool for some customers, organizing their production capacity and scheduling activities through simulations. This digital twin is integrated with the manufacturing technologies in a flexible production line.

Concerning external representation, connecting other technologies as complementors and add-ons in the flexible through the digital twin demands a commitment and partnerships with systems integrators and different technology providers. Company A develops advanced pneumatic and automated systems and the digital twin. Still, the various robots, CNC machines, and other manufacturing technologies are set by third parties integrated into this solution provided to the customer. Therefore, this platform involves other players providing external support for its operations. Finally, regarding knowledge transformation, as this platform integrates many technologies and is based on simulation, it is a powerful tool to experiment and test new potential configurations of the production lines and manufacturing processing activities, which boost the learning capacity of the company and the knowledge that it can create on the manufacturing activities.

4.1.1.2. Using 3D printers as platforms. Company F adopted additive manufacturing through 3D printers to reshape the possibilities in manufacturing and achieve new businesses through the connection with its customers. By adopting a production model centered on 3D printing, the company configurated a system of technologies that depend and work interconnected with the 3D printing manufacturing network. Firstly, the company adopted AI-based design tools to produce product components that can take advantage of additive manufacturing through 3D printers. Such design tools receive the orders from the customers, consider the parameters of the factory's 3D printing manufacturing network, and define the different configuration options to be delivered to each 3D printer. On the other side, the company's main customers can use the customer software interface, which allows them to customize the parts manufactured in the 3D printers. This means that the product parts can be produced either by the designers or the customers, following predefined standards directly sent to the 3D printing manufacturing network.

In this case, the 3D printing network operates as a central platform that coordinates the production activity and integrates software designs and customization interfaces to deliver product parts to the customer. This behaves as a task coordination system among such technologies. The information collection and processing happen around the platform and is fed into this platform through the design tools and customization interface. At the same time, the 3D printers integrate the information and transform it into delivered production parts. Regarding external representation, this platform connects the customers directly to the manufacturing process. It promotes co-creation activities for product design, allowing task coordination by incrementing the product development process with their own requirements. It also enables the external representation by integrating other technologies, such as CNC machines and robots that can produce complementary components to be added to the additive manufacturing outputs. Finally, regarding knowledge transformation, this platform enhances knowledge sharing between manufacturers and customers through customization opportunities through crowdsourcing practices that integrate user inputs for product design in its manufacturing.

4.1.1.3. Main findings for networked manufacturing operations platforms. We represent the two types of technologies identified as platforms for networked manufacturing operations in Fig. 3(A) and (B). This figure shows the boundary-spanning perspective of these platforms, considering how they are positioned in their interface with the surrounding technologies that are interconnected with them. Moreover, the picture represents the technologies and their relationships with the production flow. First, Digital Twin is shown as a technology that integrates several other manufacturing processing technologies like robots and CNC machines. As explained in Section 4.1.1, this technology allows coordination and integration. However, the platform is not essential for the operation of the other technologies. In other words, technologies like robots or CNCs can operate in a production flow without this technology, but they achieve a higher level of operation when integrated around this platform. Therefore, this is a type of platform that allows the integration of several technologies but is not essential to the production flow. Moreover, the other technologies are not in line with the production flow because they can serve different processes and not necessarily to a unique production line. Even when they are not necessarily aligned in a production line, this platform operates by exchanging information and coordinating the tasks.

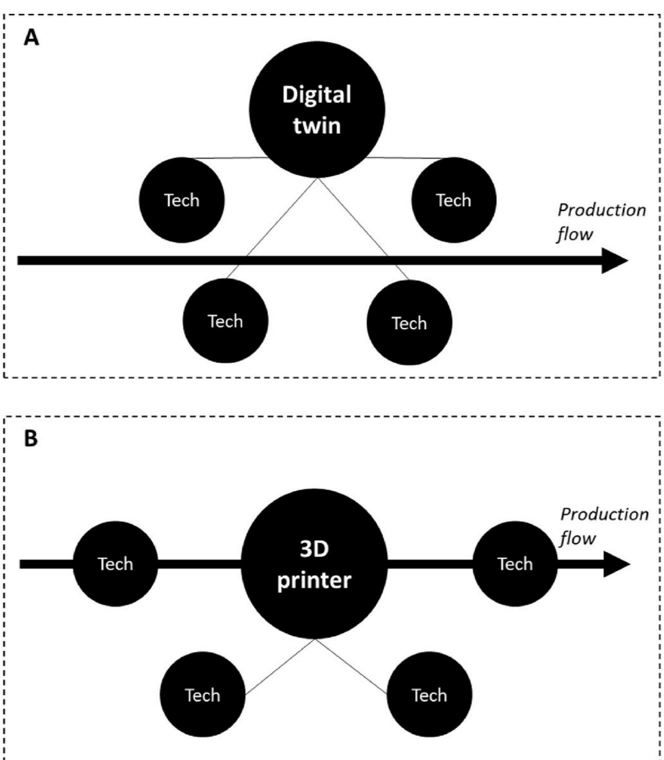

Fig. 3. Schematic representation of technologies working as platforms in Networked Manufacturing Operations: (A) Digital twin as a platform, (B) 3D printers as a platform. Notation: Black balls notated with ‘Tech’ represent generic technologies connected to the platform. Fine lines represent the connections between technologies and platforms. The bold arrow represents the production flow.

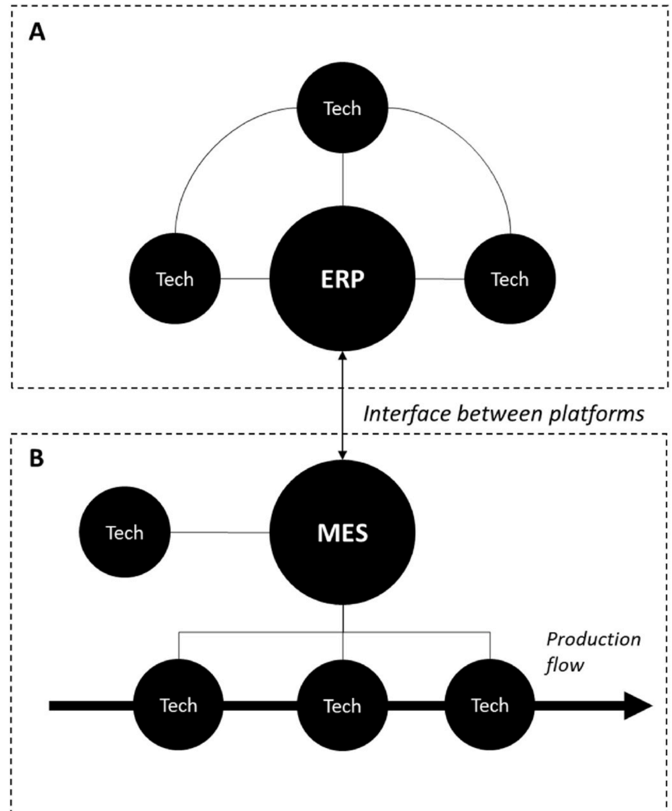

Fig. 4. Schematic representation of technologies working as platforms for Vertical Integration: (A) ERP as a platform, (B) MES as a platform. Notation: Black balls notated with ‘Tech’ represent generic technologies connected to the platform. Fine lines represent the connections between technologies and platforms. The bold arrow represents the production flow.

On the other hand, 3D printers can work as stand-alone technologies, as part of the digital twin platform of Fig. 3 (A), or as a central platform for networked manufacturing operations. This happens when the company is oriented toward additive manufacturing, as represented in Fig. 3 (B). In such a case, the 3D printer manufacturing network becomes the central technology to operate and serve the production flow. Other technologies used in this production flow will be integrated into this platform to help the platform better. As shown in the case study, design tools and customization software are being used to maximize the potential of 3D printers. Moreover, other technologies like collaborative robots and simulation will also support this technology, as represented generically in Fig. 3 (B) by the complementary dots below the production flow. Therefore, differently from digital twins, in this case, the platform becomes predominately a ‘closed system’, i.e., a system centered around the platform to organize the production flow.

4.1.2. Vertical integration platforms

This type of platform refers to technologies that manage and integrate several informational layers of the organizational hierarchy, usually operated by various information technologies and systems. As explained next, we identified two technologies in this category working as platforms.

4.1.2.1. Using manufacturing execution systems (MES) as platforms. In the early years, Company B provided Supervisory Control and Data Acquisition (SCADA) software for data acquisition in the manufacturing industry. Considering the growing interest of its customers in Industry 4.0, the company decided to advance in developing a new solution that could help its customers integrate manufacturing data with information from different information systems. The company evolved its SCADA solution into a Manufacturing Execution System, with the novel characteristic of processing and operating with real-time data flow from the manufacturing operation. This differentiates the solution from other conventional MES that operates offline and are not usually prepared to quickly reconfigure the scheduling based on the real conditions of the production system. According to the interviewees, this differentiates the MES for Industry 4.0 from traditional MES, which has also been reported in prior research as the brain of a smart manufacturing system, being the entrance door to Industry 4.0 (Tabim et al., 2021).

Task coordination is the first main BS activity that characterizes this technology as a networked manufacturing operations platform. Manufacturing processing technologies are equipped with sensors and programmable logic controllers (PLC), which allow collect data of the operation and store them in the SCADA system. Then, the MES is responsible for consolidating such data from SCADA to provide decision-making information. Through this operation, the MES coordinates the operations of the manufacturing process since it provides an integrated view of what is happening in each manufacturing technology. The solution provided by this company is also connected to the Advanced Planning and Scheduling (APS) software, which runs the scheduling organization based on the real-time data consolidated through the MES.

Furthermore, MES can be connected with Enterprise Resource Planning (ERP) systems which operate data and information at the corporate level. Thus, the MES creates an interface between the shop floor operation and the corporate management. Furthermore, these activities require a high intensity of information *collection and processing because* the MES is, in essence, an information system oriented toward the integration of the manufacturing activities to provide vertical integration of systems. As stated by the interviewees, the main advantage of this system is that it collects and processes the information from different organizational layers, providing a systemic view of the operations of the manufacturing activities.

Moreover, using this technology requires a high commitment from its partners when applied in the operations (external representation). Different technologies must open their internal information generated to integrate with the system. In several cases, the technology can face integration challenges when some manufacturing processing technologies are closed systems for data sharing and integration. As pointed out by the company, this is changing since the customers are demanding new manufacturing technologies compatible with IoT standards, but it is still a challenge. Also, because this technology needs many add-ons to perform industrial tasks, like integrating ERPs and APS, other technology providers and suppliers require a high commitment (external representation). This is necessary because they need to coordinate efforts (task coordination) to make different technologies operate organically through MES commands. Finally, regarding knowledge transformation, the fact that the technology integrates information and data from various sources to support manufacturing decision-making is a key part of the knowledge transformation in the operations. Through this technology, the company can advance in its vertical integration, which is a necessary step to know better what is happening in the whole system and learn about the systemic behavior of the operations.

4.1.2.2. Using enterprise resource planning system (ERP) as platforms. Company G is a European multinational manufacturer of trucks and buses. The company adopted a total vertical integration approach in which they used the technologies reported in Section 4.2.1 supported by MES and moved one step forward by integrating MES with the corporate level through an ERP system. However, the company approach was centered on the ERP since it also connected the computer-aided design (CAD) and computer-aided engineering (CAE) software to the ERP, as well as the information and data originated in several departments necessary to manage the company's resources.

We classified this case as a vertical integration platform due to the BS activities performed by Company G's ERP system. This platform shows high *information collection and processing* by integrating functional departments using the same system. All data inside Company G is visualized and disseminated in real-time through this platform. Moreover, in what comes to *external representation*, this platform achieves at least some results when applied in external environments. For instance, Company G works with the concept of raw material traceability through information sharing with its suppliers and subsidiaries having certain commitment from its partners in its supply chain. However, this external representation is limited to data sharing and does not enable a complete information management system.

This platform aligns all company departments and subsidiaries (internal horizontal integration) with task *coordination* by synchronizing the workflow in all units through information sharing. As mentioned before, it also synchronizes inputs and outputs from other systems used for purchasing, supply management, human resources, or even product design. Besides, in terms of external collaboration, this platform works with traceability, allowing for some coordination of replacement parts with suppliers. For *knowledge transformation*, this platform enables the company to respond appropriately and with agility to changing market signals and track new opportunities by aligning all company departments with the worldwide subsidiaries.

4.1.2.3. Main findings for vertical integration platforms. We represent the two types of technologies identified as platforms for vertical integration in Fig. 4(A) and (B). This figure shows the boundary-spanning perspective of these platforms, considering how they are positioned in their interface with the surrounding technologies that are interconnected with them. Furthermore, unlike the networked manufacturing operations platforms (Section 4.1), our findings show that these two platforms are interdependent in creating vertical integration. This was especially highlighted in the case reported in Section 4.2.2. While both technologies operate as stand-alone platforms, one oriented to shop floor activities (Fig. 4-B) and the other oriented to corporate resources management (Fig. 4-A), both need to be integrated when vertical integration is pursued. Therefore, there is an integration of surroundings technologies with the platforms and integration between the platforms, connecting two ecosystems of technologies.

There are also differences in how these technologies operate as platforms. First, ERP works with other technologies, but it is predominantly as a central system because the different department software interfaces operate around the platform to organize the information flow. On the other hand, the MES allows data collection from any manufacturing equipment provided by connectivity. In this case, the surrounding technologies execute the production flow operations, and the MES acts as a supporting technology (not a central system for the operation) that enables better coordination and information synchronization. Moreover, Fig. 4-B shows other potential technologies connected to the MES as supporting tools, like an APS or an AI-based algorithm to analyze the MES indicators and predict failures or additional information on the production behavior.

4.1.3. End-to-end engineering platforms

This type of platform refers to technologies that work as orchestrators of several existing databases and technologies from the functional areas to create a unique view of the company. As explained next, we identified one technology in this category working as a platform.

4.1.3.1. Using product lifecycle management systems as platforms. Company E is a European multinational with a vast product, service, software, and technology portfolio. Focusing on Industry 4.0 end-to-end engineering, the company provides Product Lifecycle Management (PLM) software that runs with IoT and cloud solutions to integrate the different functional data and information for the product development process, considering the main departmental stages this process must go through, including marketing, product design, material purchasing, manufacturing, and after-sales services. The system is responsible for managing the full information along the product lifecycle stages, having as a key feature its capacity to connect external partners to share information in projects managed by such a system. Consequently, this platform creates an ecosystem of technologies whose interface is the databases they make about the product characteristics.

Regarding the BS activities, first, we consider *information collection and processing*. The PLM system is mainly a system that organizes and integrates product-related databases along the product lifecycle. Therefore, it creates interfaces and interconnections with the database structure built from different technologies. In the case of *task coordination*, the system synchronizes various operational activities conducted through software linked to the PLM through the shared databases. The PLM enables project lifecycle management by integrating several process steps. The system also allows *external representation because* the company's PLM generates other technologies, including digital twin and ERP, as complementors and add-ons to create a broader ecosystem of technologies. Lastly, as many partners can co-develop solutions for knowledge transformation, there are many interdependencies in this platform. This means that some partners are also customers or intermediaries in the platform. This is supported by a complete overview of the product lifecycle stages in each project. These end-to-end solutions are built through access to the platform's other capabilities and analytical tools.

4.1.3.2. Main findings for end-to-end engineering platforms. We represent the PLM technology identified as a platform for end-to-end engineering in Fig. 5. This figure shows the boundary-spanning perspective of this platform, considering how it is positioned in the interface with the surrounding technologies that are interconnected with it. As shown in this figure, PLM operates as a central coordination platform with other technologies such as CAD/CAE, purchasing systems, or manufacturing systems through the interfaces of the different databases of such technologies. In this sense, PLM works as a platform that integrates data and creates information and workflow for the product lifecycle.

4.1.4. Horizontal integration platforms

This type of platform refers to technologies that operate as technology environments for integrating and orchestrating the company information with third parties (e.g., suppliers and buyers). In this section, we investigated two different cases, IoT platforms, and Cloud platforms. Although they can be differentiated regarding the emphasis of each described below, it is important to highlight that several market brands have them integrated into a single solution of IoT/Cloud. Moreover, we represent their highest potential as platforms for horizontal integration and the creation of broader ecosystems. Nonetheless, such generic platforms are also present, supporting the aforementioned internal technology systems of the company discussed in the other platforms of our results. Moreover, these two technologies are usually known in commercial applications as platforms, the most traditional type of platforms for Industry 4.0.

4.1.4.1. Using IoT systems as platforms. Company C provides Industry 4.0 IoT solutions. Company C connects hardware, cloud, and high-level software with an IoT platform to develop advanced solutions. These solutions have evolved into IoT platforms to provide customers with intelligence and connectivity. This IoT platform is composed of technology-enabled entities allowing for the connection of several apps, BI (business intelligence) commands, and add-ons that help manage data from a company and synchronize with supply chain partners. Companies achieve external horizontal integration because their users (platform owners and partners) have access to data, technology, and several tools for coordinating decision-making through information management. Although this platform comprises a cloud system, its main emphasis relies on the capability of connecting and collecting data from smart devices (machines, equipment, etc.) that are located either internally in the company or externally in the value network.

Regarding information *collection and processing*, its IoT systems allow for connectivity between supply chain partners for joint decision-making, thus creating a Smart Supply Chain. Smart Supply Chain is designed through information management from this IoT platform that controls and monitors the data flow from the focal company and its activities with supply chain partners. Concerning *external representation*, the IoT platform achieves a high commitment from external partners by connecting systems and providing information management and

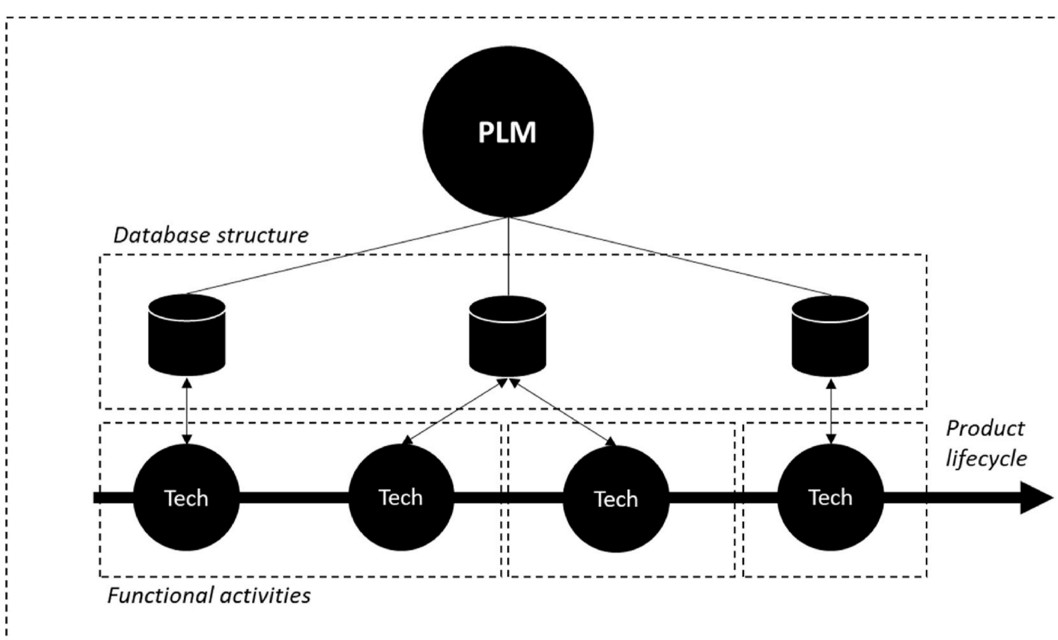

Fig. 5. Schematic representation of PLM working as a platform for End-to-End Engineering. Notation: Black balls notated with 'Tech' represent generic technologies connected to the platform. Fine lines represent the connections between technologies and platforms. The bold arrow represents the production flow.

analytical tools. Because this is an open environment, cybersecurity is a concern, conditioning the access of its partners to data acquisition and analytical tools to contractual relationships. These partnerships through contracts are accomplished to guarantee cybersecurity and user access to analytical tools for the supply chain management.

Moreover, *this platform enhances task coordination* in the supply chain because it supports big data and analytical tools to overcome breakouts in the chain. Finally, regarding *knowledge transformation*, this platform has an open environment for the leading company to pursue external capabilities to complement its product/service development. However, it still lacks connectivity with customers for end-to-end solutions. Therefore, some of the main limitations of this platform are the difficulty in managing the information from customers and consequently aligning and coordinating tasks in the supply chain.

4.1.4.2. Using cloud systems as platforms. Company D is a multinational company with a Cloud + AI group division that develops a cloud platform. This cloud platform offers analytical tools such as AI algorithms and IoT connections for its customers to build their apps and solutions. So, this company is strongly engaged in Industry 4.0 high-tech environments through a cloud platform for its customers to develop their own solutions. Moreover, this platform follows an open approach, allowing it to plug-in new technologies and apps to improve its operational capability for its users. In this sense, this platform connects all systems in manufacturing, enabling the insertion of new technologies as add-ons. One of the greatest potentials of such a platform is that it has as a primary goal of information sharing. Thus, when analyzing the case, we perceived that this cloud platform was primarily designed for information management, whereas the other technologies connected provide such information. In this sense, the main difference between this platform regarding the IoT platform is that its core activity relies on data sharing and on the potential apps that can be developed to analyze such data and information sharing, although IoT devices also feed it.

Regarding BS activities, this platform operates as a general server where information *collection and processing* are shared among its users. *External representation* occurs inside this platform through contracts, as it requires commitment from its users who share data in the same space with common goals (e.g., app development). Regarding *task coordination*, this platform offers software applications for product and software development, requiring coordination between third parties and the platform owner. Finally, about *knowledge transformation*, cloud platforms provide a set of analytical tools helping the company to develop its own solutions and improve them by using advanced algorithms in the AI field at the corporate level. This platform integrates suppliers for complementary capabilities and parts replacement during the product development process. However, such a platform still has some limitations: synchronizing information with customers to create and manage collaborative practices/activities.

4.1.4.3. Main findings for horizontal integration platforms. We represent the two types of technologies identified as platforms for horizontal integration in Fig. 6(A) and (B). This figure shows the boundary-spanning perspective of these platforms, considering how they are positioned in their interface with the surrounding technologies that are interconnected with them. In Fig. 6 (A), we show that Cloud platforms integrate different technologies and organizational activities by consolidating them into a cloud solution that combines data and provides various services based on an external ecosystem of apps and APIs. Moreover, the cloud platform connects with the supply chain and other partners, creating a common ground for information sharing. On the other hand, Fig. 6 (B) shows that IoT platforms are focused on industrial functions connecting the machines with the platform and with the external activities of the supply chain. As shown in Fig. 6, IoT platforms can also be integrated into Cloud platforms creating an integrated system between both. The figure shows that while Cloud platforms are more oriented toward the external boundaries of the organization, operating with business ecosystems, IoT platforms are mainly in the interface between intra- and inter-organizational industrial processes. However, both solutions connect with the external value network to provide horizontal integration.

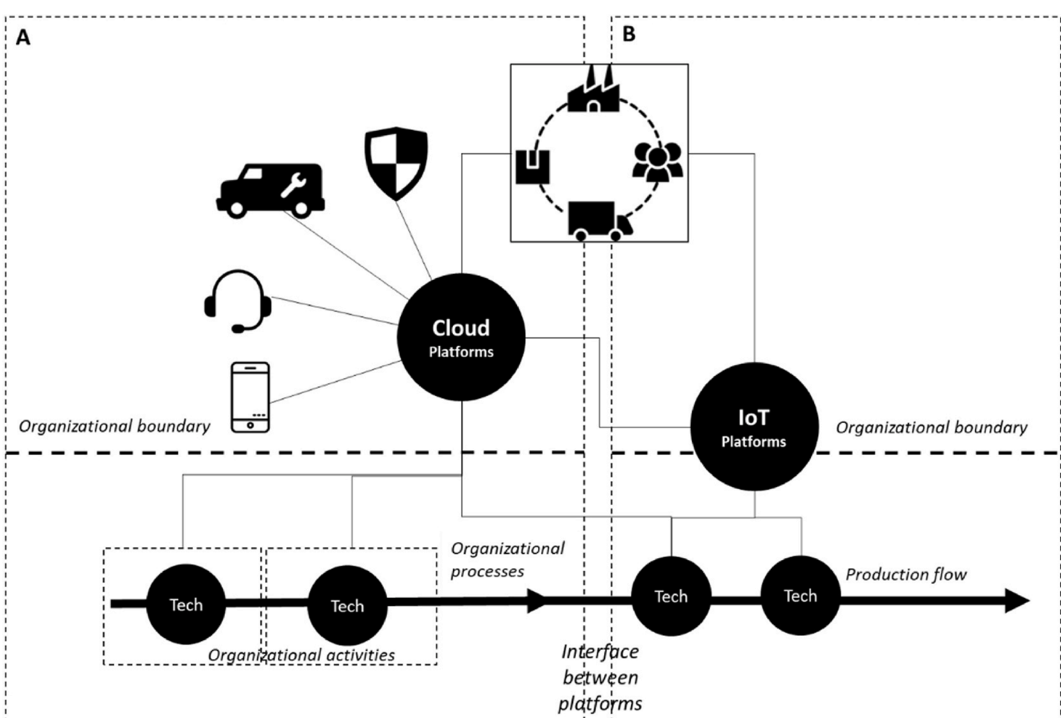

Fig. 6. Schematic representation of IoT and Cloud systems working as a platform for Horizontal Integration. Notation: Black balls notated with 'Tech' represent generic technologies connected to the platform. Fine lines represent the connections between technologies and platforms. The bold arrow represents the production flow.

4.2. Consolidation of Industry 4.0 platforms characteristics

We also analyzed the key elements discussed in the different platform perspectives (engineering, organizational and economic) that help characterize the operation model and impacts of the technology platforms, as summarized in Table 5.

First, the engineering perspective describes the different elements of the technology architecture, which was already described in the case studies. While the BS activities define the core architecture, we also considered the peripherical architecture, i.e., the integrated technologies to operate with the platform as a system in the Industry 4.0 domain. The interviews also allowed us to differentiate between contributors, i.e., main technologies that contribute to the platform's core value, and complementors, which are technologies that can create an ecosystem of value but are not necessarily the core of the system. The table shows that sometimes contributors can be limited, like in the case of ERP, PLM, and IoT/Cloud systems, which tend to be closed systems developed by the technology provider.

Regarding the organizational perspective, Table 5 shows the relationship between specialization and complementary resources regarding each platform. Operational platforms are more related to the internal processes and need more specialized knowledge of the technology implementor due to a higher customization requirement, which is complemented by the internal knowledge of the technology adopter. On the other hand, external platform layers are more standardized and require more complementarity of systems integrators and from other external complementors.

Regarding the economic perspective (Table 5), operational and systems integration platforms show a more internal and limited network effect because they embrace a limited number of internal technologies that the company owns. On the other hand, the more open and external the Industry 4.0 platform is, the less controlled this network effect is, and the more external it is. This means that for more external platforms, like in the case of horizontal integration, different complementors have the opportunity to create solutions and, therefore, more network effects. Finally, switching costs also follow this internal-external perspective: the technologies investigated showed that internal technologies require more process adaptation, creating a higher interdependency between the technology and the operations. This creates higher switching costs due to such adaptation to a specific technology. On the other hand, the more open and standardized the platform is, like in IoT and Cloud system platforms, the adaptation required is lower due to plug-and-play solutions, but the switching costs can be more present in the partners' engagement. For instance, the solution provided by Company D requires an engagement of suppliers and customers around the platform adopted by the manufacturer (customer of Company D). Future changes to other

Table 5
Analysis of the platform characteristics based on key elements from different platform perspectives.

	Core architecture	Networked Manufacturing Operation		Vertical Integration		End-to-End Engineering	Horizontal Integration
		Digital twin	3D printers	MES	ERP	PLM	IoT/Cloud Systems
Engineering perspective	Peripherical architecture	Manufacturing processing techs like Robots and CNCs	Customization interfaces, and manufacturing processing techs like Robots and CNCs	Manufacturing processing technologies connected to the MES	MES and external suppliers' systems	Product design (CAD and CAE), purchasing systems, manufacturing systems, etc.	Apps, BI commands, and add-ons
	Contributors	Simulation software and sensors	AI-based design tools, 3D printing networks	Sensors, SCADA, and, ERPs	Apps and solutions ran as modules of the ERP (limited)	AI-based design tools (limited)	Tend to be closed systems for industrial applications
	Complementors	Developers of other information systems like PLM ran over the digital twin	Developers of customization apps for the use of 3D printers' network	AI algorithms for applications like maintenance and quality control	CAD and CAE software, and analytic tools integrated to the ERP.	3D printers, Digital Twins, MES	A high variety of apps and solutions can be added
Organizational perspective	Specialization	Requires high specialization from the technology implementor due to customization	Requires high specialization from the technology implementor due to customization	Basic solutions are sometimes developed by the own company's IT team	Requires moderate specialization due to standardized solutions	Requires moderate specialization due to standardized solutions	Are less specialized due to plug-and-play solutions
	Complementarity	Requires process knowledge from the adopter	Requires resources from complementors (customization interfaces, design software, etc.)	Requires automation knowledge from systems integrators	Requires automation knowledge from systems integrators	Requires knowledge of processes from the engineering and manufacturing teams	Require resources from complementors, which is essential for their value.
Economic perspective	Network effects	Are internal and controlled: Creates more value when more parts of the plant are digitalized and integrated with the digital twins	Are internal and controlled: Creates more value when more 3D printers are integrated with the network	Are internal and controlled: Creates more value when more parts of the plant are connected to the system	Are internal and external: Creates more value when more processes, suppliers and customers are integrated with the system	Are internal and external (limited): Creates more value when more processes and external actors related to the product lifecycle, like vendors, are integrated.	Are external and high: Creates more value when more ecosystems partners are connected and when more solutions are developed for the platform
	Switching costs	Switching costs become higher the more time is spent to create digital libraries of the physical assets.	Switching costs are moderate to high and related to the investment and to the manufacturing model adopted through 3D printing, which affects the production flow	Switching costs are moderate, limited to investments	Switching costs are high due to the high investments required and the business process fit required during the implementation	Switching costs are high due to the high investments required and the business process fit required during the implementation	Due to their plug-and-play profile, switching costs tend to be lower than other Industry 4.0 platforms

technologies are limited because they may need new agreements among these partners in the ecosystem.

We show these results from Table 5 in a graphical representation of generic patterns for the Industry 4.0 platform layering as a value chain (Fig. 7). These patterns represent the extremes of the variations that one can find among the different platforms used in the Industry 4.0 context.

5. Discussions

Our results highlight seven technologies that work as platforms according to the BS activities. The results show how these platforms contribute to the Industry 4.0 key features. As we explained in our theoretical background, much attention has been given to economic and market platforms for products and services in the digital transformation context. Still, little is known regarding platforms for Industry 4.0. In this sense, our results showed that these seven platform types could contribute to the different features of the Industry 4.0 concept. Our results suggest that the different Industry 4.0 features can effectively be built around platforms. These platforms meet each of these key features and connect the ecosystem of technologies for the operationalization of the features, namely networked manufacturing operations, vertical integration, end-to-end engineering, and horizontal integration.

Regarding the specific characteristics of the technologies considered as platforms, we show that some information technologies like digital twins, MES, ERP, and PLM operate as platforms in the Industry 4.0 context. Tabim et al. (2021) have stressed the central element that the integration of information systems has in the Industry 4.0 journey. In the same vein, Frank et al. (2019) and Dalenogare et al. (2018) showed through empirical data that some of these technologies are in the first implementation step when companies start an Industry 4.0 journey. Our results complement such findings, providing a better understanding of why such technologies are so important in the plan of an Industry 4.0 roadmap. As they can work as platforms, they provide a common ground for the operation of an ecosystem of technologies integrated with them. This means that these technologies become orchestrators of different parts of the Industry 4.0 concept. An important contribution, in this sense, is that our results clarify which key feature of Industry 4.0 is supported by each of these investigated platforms. Therefore, it is not just a matter of implementing them to start the Industry 4.0 journey, but managers need to understand their contributions to the system. For instance, when companies aim to integrate better the external value network, general-purpose platforms oriented toward the integration of the value network is required. In this case, generic platforms such as cloud and IoT support this aim. On the other hand, digital twins can work as an important platform when the focus is coordinating internal operations of equipment and machines based on frequent layout improvements and production flow changes. Therefore, the nuances between the different platform's goals and applications must be considered, as shown in our findings, especially when we considered platform characteristics and differences regarding key elements from the engineering, organizational, and economic perspective of the platforms (Table 5 and Fig. 7).

Moreover, our results show that operations technologies can also act as platforms, as in the case of 3D printers, which can operate a whole ecosystem of technologies and processes toward additive manufacturing. In a previous study, Siqin et al. (2022) showed how this technology is deeply connected with platform business models, supporting the integration between manufacturing and customers. In this same vein, we show that 3D printing can become a manufacturing platform to attend such business models since it can create an ecosystem of solutions oriented to product customization, which is only feasible through this platform characteristic. Such a result contributes to recent empirical observations from Benitez et al. (2020). They pointed out that additive manufacturing was emerging as a platform to connect various software and hardware for new types of business solutions. Also, we found that the digital twin is another technology that can work as a platform in the manufacturing field. This technology was previously pointed out as a potential Industry 4.0 platform by Redeker et al. (2021), who explained the architecture of elements composing this technology. In our case, we analyzed how this technology can operate as a platform and showed the different BS activities involving its role as a platform in a manufacturing environment. The main function of this platform is to create a flexible manufacturing system through the coordination and real-time synchronization of assets (Fan et al., 2021). Therefore, our results exemplified how such flexibility is achieved when used as a platform.

Regarding IoT and cloud platforms, these have been the most discussed type of platforms in the literature. The study from Frank et al.

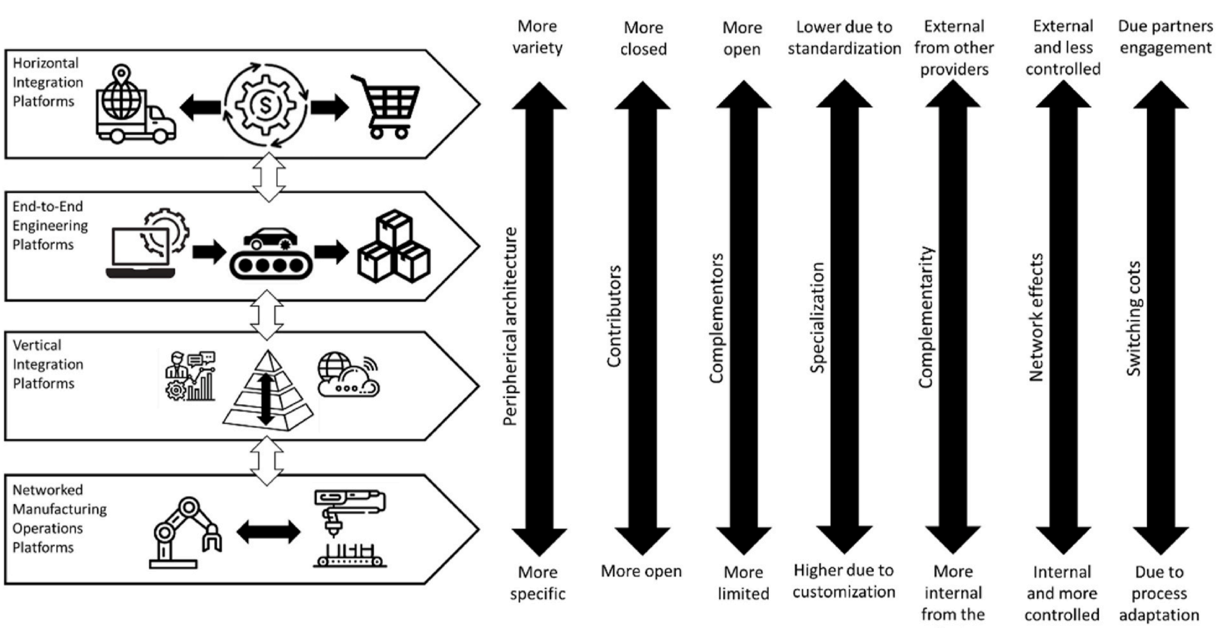

Fig. 7. Schematic representation of Industry 4.0 layers of platforms and their main characteristics according to different perspectives (engineering, organizational and economics).

(2019) conceptualized IoT and cloud as two base technologies of Industry 4.0 since they support the different technological applications of Industry 4.0. Also, Meindl et al. (2021) reviewed over 5000 articles over the ten years of Industry 4.0 and showed that IoT and Cloud are essential technologies operating as generic platforms in almost every Industry 4.0 application. Therefore, two generic platforms can be present in the different Industry 4.0 key features addressed in our study. However, following the same reasoning as Frank et al. (2019), we discriminated in our analysis of these two types of platforms as end solutions from their role operating in the backend of other technologies. Therefore, when we addressed vertical integration, we focused on an advanced implementation of ERP and MES in the Industry 4.0 context, which is assumed to contain IoT and Cloud (Tabim et al., 2021).

On the other hand, our results focused on the main role of IoT and Cloud platforms in the integration of the value network through horizontal integration. As suggested in other studies on IoT and cloud platforms, the more generic and open the platform is, the better for integrating an external ecosystem of actors with their technologies (Botta et al., 2016; Cavalcante et al., 2016). We show in our results how they connect to the external environment and create network effects by bridging internal activities with external ecosystems. Moreover, unlike the other platforms closer due to their specific task orientation, IoT and cloud are generic and open, becoming not only a technology platform but also an innovation platform for the external ecosystem of actors that cooperate with the company (Cusumano, 2019).

The last consideration regarding our findings is the need to consider a systemic view of the Industry 4.0 platforms integration. Industry 4.0 should be regarded as a technology model oriented through the key features as addressed in our platform typology (Kagermann et al., 2013). However, we must consider that such features should be pursued together, configuring a technological system to create a digital enterprise (Frank et al., 2019). Therefore, we summarize the association among the different platforms in the representation of Fig. 8. Also, Fig. 8 represents the platforms according to how they are related to the Industry 4.0 features and the different organizational activities as value adding layers.

The first layer represented in Fig. 8 is 'operational activities, which are supported by *Networked Manufacturing Operation* platforms. Such platforms are represented by two technologies: digital twin and 3D printers, as explained in our results. However, in some cases, the digital twin can also be used to operate 3D printers (Li et al., 2021), and, therefore, we represented both platforms as interconnected. At the second organizational layer, we considered cross-functional activities oriented to the *End-to-End Engineering platform* (PLM systems). We described this platform as interconnected with many of the other platforms. PLM can be incorporated and used in a virtual representation of the product and its production (VanDerHorn and Mahadevan, 2021).

Moreover, as demonstrated by Avvaru et al. (2020), PLM can also be integrated with MES and ERP systems in an Industry 4.0 architecture in which the three platforms are integrated and share a common knowledge base system to transfer data among all them. Third, we consider Vertical *Integration* platforms, which connect mainly MES and ERP, i.e., operational with corporate activities (Tabim et al., 2021). At the same time, MES supports operations technologies, including 3D printing, while ERP transcends the organizational boundary and can integrate data from external supply chain actors and other partners. Finally, Cloud and IoT platforms are represented in Fig. 8 as supporting platforms for the other inter-organizational platforms. At the same time, they also are oriented to their main contribution, which is connecting the value network as Horizontal Integration platforms. We represented these two platforms in another color due to their twofold functionality working as the base technology for the other inter-organizational platforms and as an end solution for horizontal integration.

Thus, the representation of Fig. 8 helps to understand how these platforms are related when using a perspective of platform layering as a value chain. This complements the summary of findings of Fig. 7, where we show the variation of platform characteristics and impacts along these layers, which is also provided in detail in Table 5.

6. Conclusions

Our study contributed to the characterization and definition of Industry 4.0 platforms. We used a platform layering as a value chain approach to considered four distinct platform configurations based on the Industry 4.0 key features: Networked Manufacturing Operations, Vertical Integration, End-to-End Engineering, and Horizontal Integration platforms. We classified Industry 4.0 technologies as platforms into these categories using a boundary-spanning perspective that considers how a certain technology connects with its surroundings. The BS perspective allowed us to identify four activities conducted by these platforms: information collection and processing, task coordination, external representation, and knowledge transformation. We find seven leading technologies that can be defined as Industry 4.0 platforms in such categories and activities: Digital twin, 3D printer, PLM, MES, ERP, Cloud, and IoT platforms. We then analyzed these platforms using three main platforms perspectives from the literature (engineering,

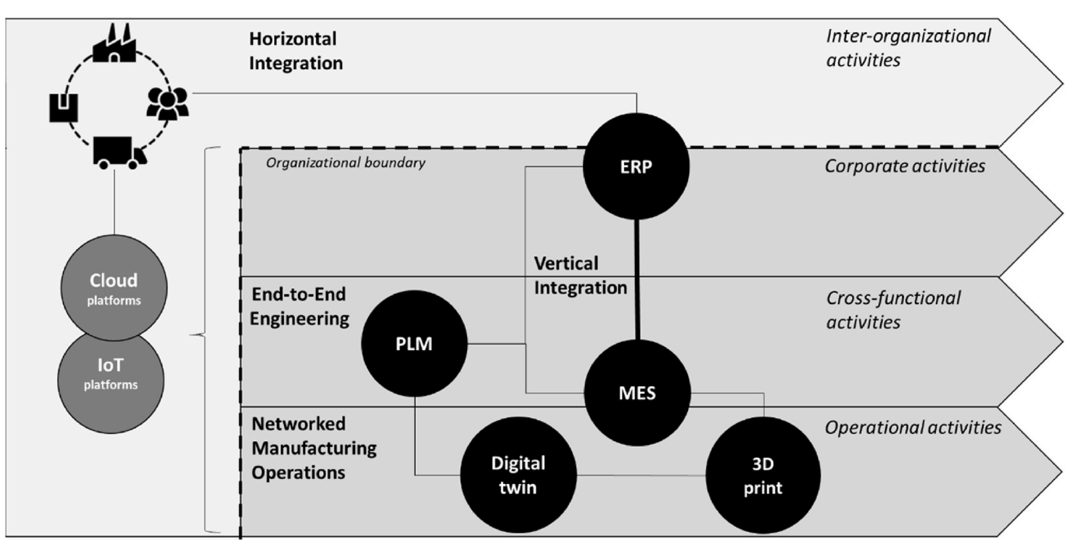

Fig. 8. A systemic view of the interfaces between Industry 4.0 platforms. Note: Platform categories are highlighted in bold, and organizational and inter-organizational layers of activities are highlighted in italic.

organizational, and economic), which allowed us to discuss how these different platforms vary in terms of peripherical architecture, contributors and complementors, specialization and complementarity, and network effects and switching costs. Our study shows how these platforms are structured with other technologies according to their aim in the Industry 4.0 context. It also shows how different platforms are interrelated to build a system of platforms. This is the first study that analyzes and categorizes Industry 4.0 platforms, providing a clear framework of the type of platforms and their contributions to the Industry 4.0 key features.

6.1. Theoretical contribution

We highlight three main theoretical contributions of our study. First, we showed that although, in practice, only IoT and cloud systems are named 'platforms', there are different types of platforms around which the Industry 4.0 system can be designed. We showed how this provides value for companies since they can achieve higher levels of business integration, which is a keystone of the Industry 4.0 concept. Thus, we further extend the understanding of the 'integration' concept in Industry 4.0 field. We explore this using the platform concept in the technology systems view (engineering perspective) by explaining how different Industry 4.0 technologies may connect with their surroundings and turn into platforms. By providing a clear taxonomy of the Industry 4.0 platform, our study encourages scholars to open new avenues of research in the Industry 4.0 domain, focusing on the system integration of technologies around platforms to build Industry 4.0 journeys rather than by investigating a set of stand-alone technologies as it has been done mainly in the state-of-the-art. Second, we show that some technologies can operate for a single purpose or, in fact, as platforms, depending on how the company designs its use. This is the case of a 3D printer, which can be used as a single technology for the production process or as a pivot, a central platform of the manufacturing system that will operate based on it, as shown in our case study. Therefore, scholars can find initial evidence in this study to investigate situations when technologies are used as platforms. The framework provided with the taxonomy of platforms is useful to this type and direction of research. Third, we show patterns across the platforms regarding the key elements of the different platform perspectives by comparing the differences in terms of peripherical architecture, contributors vs. complementors, spatialization vs. complementarity, and network effects vs. switching costs. We explain the differences that serve scholars as a starting point to investigate such variations and profiles in detail to answer how a platform ecosystem should be managed and how platforms can be promoted by considering such characteristics. In other words, the literature should not consider only functional requirements for platforms. Our results show that several elements must be considered and must be managed with a proper approach for a successful implementation of platforms. Such implementation deserves future investigations based on our results.

6.2. Practical implications

The platform view can help managers and practitioners look inside their industrial environment and understand how these technologies can be organized. The main implication for practitioners is that we call for a focus shift in the Industry 4.0 implementation journey. Such implementation journeys are based on maturity levels that companies aim to achieve and are oriented to different operational targets, like productivity or flexibility (Enrique et al., 2022a, 2022b). In this sense, practitioners tend to focus on the immediate and main functionality each technology can provide to the journey. Instead, practitioners should build their Industry 4.0 journey around platforms to achieve the features presented in this study. This will help create a solid background for integrating many other technologies. Otherwise, companies may face the usual problem of technology limitation due to the lack of interconnectivity and interoperability with other necessary technologies. As shown in our results, the orientation toward these various platforms can help avoid this and create an integrative view of technologies for Industry 4.0. In addition, practitioners can learn the limits of their technological environments and to which extent they can reach information management. To this end, the BS perspective help to understand to what extent information is managed in each platform.

6.3. Limitations and future research

One limitation of this study is that we were not exhaustive with the whole set of technologies to ensure that there are no other platforms. Moreover, we did not investigate several cases for each technology to consider the extension of these technologies as platforms. In this sense, we can only describe those investigated here and to the extent of their use in the cases analyzed. Future studies can further this research by expanding this study and systematizing our findings in quantitative research to help understand the extent of such application in companies. In other words, new research could specifically determine the number of companies using such platforms as a platform rather than as a single technology and the level of integration of such platforms to other technologies in the business systems. Another research limitation was the platform perspective adopted since we focused only on industry platforms in the technology systems view. Some perspectives like two-sided and multi-sided markets from transaction economics (e.g., Rochet and Tirole, 2003) could be linked to BS activities, helping to deepen the understanding of how platforms shape businesses in the Industry 4.0 context. Finally, we only considered the use of platforms in companies located in Brazil. We believe that the technology perspective of our study should not be affected by the country's context since we considered advanced companies, most multinationals with global benchmarking factories in this country. However, future studies should focus on understanding Industry 4.0 platform diffusion. In such a case, they need to consider the national context due to this country's early stages of Industry 4.0 maturity (Dalenogare et al., 2018).

Data availability

The data that has been used is confidential.

Acknowledgments

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Appendix A. Research codification protocol

Step 1 - Profile: Identifying Industry 4.0 technology (ies) and core business					
Type: Technology provider (.) Technology adopter (.) Technology (ies): Business:					
Step 2 – Industry 4.0 technologies analysis and case study selection: Identifying if the technology performs BS activities					
I4.0 technology/BS activities	Information collection and processing	External representation	Task coordination	Knowledge transformation	Conclusion
Technology 1	X	X	X	X	Platform
Technology 2	X	X			No
Technology 3		X		X	No
…					…
Step 3 – Data triangulation: Identifying general aspects related to this technology acting as a platform					
Technology provider: Elements and examples identified in providers and their customers (interviews and secondary data). Technology adopter: Elements and examples identified in adopters (interviews, visits, and secondary data).					
Step 4 - Platform type: Defining the scope in which the platform operates by analyzing where BS activities are stronger in the selected case					
BS activities (for each technology)	Information flow Inside borders (operations)	Inside borders (across information layers)	Inside borders (across departments)	Outside borders (with external partners)	Conclusion
Information collection and processing	X				Networked Manufacturing Operation
External representation					
Task coordination	X				
Knowledge transformation					

Appendix B. Semi-structured interview guideline

General information.

1. Please briefly introduce your company background and involvement with Industry 4.0.

Questions about Industry 4.0 technologies [For technology providers].

2. Please describe which Industry 4.0 technologies your company provides and how this (these) technology (ies) operate(s) for your customers.
3. Please specify the main advantages for companies to acquire your Industry 4.0 technology (ies).

Questions about Industry 4.0 technologies [For technology adopters].

1. Please describe which Industry 4.0 technology (ies) your company adopted and the reason(s).
2. Please clarify how your firm works with this (these) technology (ies).

Questions about BS activities [For both respondents].

1. Please, describe how this (these) technology (ies) capture(s), process (es), and disseminate(s) information *(information collection and processing)* at the company, supply chain and/or ecosystem.
2. Please describe how this (these) technology (ies) help(s) to engage *(external representation)* departments and external partners for value creation at the company, supply chain and/or ecosystem.
3. Please describe how this (these) technology (ies) coordinate(s) *(task coordination)* processes, tasks, decisions, and partners at company, supply chain and/or ecosystem.
4. Please describe how this (these) technology (ies) transform(s) information *(knowledge transformation)* into value at the company, supply chain and/or ecosystem.

Appendix C. Most relevant quotations from the interviewees

Sample quotes	Platform case	Technology	Enterprise	Respondent's occupation
"Any production line has its limits, so the problem is [that] there is no integration between the areas, all the automated areas in a company […] and that is the problem of flexibility from my point of view […] so, our company offers a flexible concept through a digital twin which manages all data from the factory."	Networked Manufacturing Operations	Digital twin	Company A	Product Portfolio Manager
"Our digital twin can simulate and manage real-time data from the Integration of pneumatic and hydraulic systems with digital devices."	Networked Manufacturing Operations	Digital twin	Company A	Product Portfolio Manager
"We offer a platform where all technologies and systems are coordinate by our digital twin, which allows flexibility through data management in manufacturing for companies."	Networked Manufacturing Operations	Digital twin	Company A	Product Portfolio Manager

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(*continued*)

Sample quotes	Platform case	Technology	Enterprise	Respondent's occupation
"We have many kinds of products, any kind of joints (modules) that we can produce, and in terms of machinery, our aerospace division has one 3D printing platform which connects our line with our customers."	Networked Manufacturing Operations	3D printer	Company F	Launch Manager Leader
"One of our biggest challenges is to convince our potential customers to interact directly with the interface of such a platform. Because it is something very new and provides interaction in CAD and modeling, our customers are not used to such a variety of tools when asking for their parts and components."	Networked Manufacturing Operations	3D printer	Company F	Launch Manager Leader
"We believe the array of processes that fall under the 'additive' umbrella will revolutionize manufacturing across every industrial sector."	Networked Manufacturing Operations	3D printer	Company F	Vice President of Engineering & Technology
"Therefore, we are working to turn this 3D printer platform into a global standard for all company units, especially the automobile branches in which, nowadays, in terms of Industry 4.0, we are only working with traceability of auto parts."	Networked Manufacturing Operations	3D printer	Company F	Vice President of Engineering & Technology
"Initially, we only worked with SCADA systems for data collection and processing. Afterward, we realized we had the know-how to develop a Manufacturing Execution System connected with the entire shop floor that manages real-time data with the support of digital devices."	Vertical Integration	MES	Company B	Development Director
"We do not offer a traditional MES where managers perform simple dashboard commands like MRP and production workflow in most cases. We provide product tracking and genealogy with real-time data management."	Vertical Integration	MES	Company B	Development Director
"Our MES solution can be considered a platform since it collects and processes the information from different organizational layers, providing a systemic view of the operations of the manufacturing activities."	Vertical Integration	MES	Company B	Development Director
"Our Enterprise Resource Planning is a platform that synchronizes inputs and outputs from other systems used for purchasing, supply management, human resources, product design, procurement, and warehouse data."	Vertical Integration	ERP	Company G	Executive Manager
"Yes, today we have a complete vertical connection, starting in simulation, going to the product demand, managing the manufacturing, supervising and sending orders to the robots, which are flexible according to customer needs […] so, we have ERP managing MES, SCADA, and other systems […], and then we have the equipment connected, using IoT, which is one of the pillars of Industry 4.0".	Vertical Integration	ERP	Company G	Executive Manager
"Because our main goal was to build our platform solution, and since the company's roadmap to Industry 4.0 is vertical integration systems, we established a platform-oriented solution using the Enterprise Resource Planning as the brain of our factory and all functional departments."	Vertical Integration	ERP	Company G	Executive Manager
"We developed a solution using our Product Lifecycle Management software as a platform that manages all product project data."	End-to-end Engineering	PLM	Company E	Business Developer Engineer
"Of course, we need other technologies like IoT, machines, and big data, but the key point is that our PLM platform manages all information from these machines and devices."	End-to-end Engineering	PLM	Company E	Business Developer Engineer
"One of the main differentials from our technological solution oriented to platform configuration is that it works with add-ons, i.e., the PLM platform receives data from all other technologies like CNCs and the ERP system to manage the product lifecycle."	End-to-end Engineering	PLM	Company E	Portfolio Development Executive
"When we developed such a solution, our main concern was how to integrate stakeholders and partners in project management to support transactions and exchanges during product planning and lifecycle."	End-to-end Engineering	PLM	Company E	Portfolio Development Executive
"We have a famous use case with a German automotive multinational company where we are developing their product platform over ours. This company will integrate production to the dealer, so from production to the dealer to IoT, and, for example, when the customer buys a car, they will know where the car is in the process; besides, part of the platform will make predictive maintenance and all the automation thing for production […] thus, we are connecting the end consumer to this platform through our PLM software to have all the links in the ecosystem."	End-to-end Engineering	PLM	Company E	Product and Marketing Engineer
"This solution was specifically designed to integrate digital transformation devices in a platform to connect partners and support the product development process."	End-to-end Engineering	PLM	Company E	Product and Marketing Engineer
"Large companies in Brazil still have a tiny amount of useable data on the manufacturing process, and our company connects all systems through our IoT platform".	Horizontal Integration	IoT systems	Company C	CEO
"During this transition process [to Industry 4.0], we shifted from being a company that sells products to one that sells intelligence through our platform to solve industrial automation problems".	Horizontal Integration	IoT systems	Company C	CEO
"We evolved from a simple IoT device connection to a platform solution for Industrial Internet of Things where all systems are connected through IoT, having interoperability, transparency, and integration, all provided by this IoT platform."	Horizontal Integration	IoT systems	Company C	CEO
"Our cloud platform is the missing link from previous IT solutions that tried connecting supply chain tiers. We can now offer a platform that fully supports data sharing among enterprises and their suppliers, especially for strategy alignment in purchasing operations and logistics."	Horizontal Integration	Cloud systems	Company D	Senior Product Manager
"The point is we do not provide the solution, we help these customers to build their solutions and, obviously, these solutions leverage our software and cloud services to work with them […] but the end consumer owns the service and resells it in its ecosystem".	Horizontal Integration	Cloud systems	Company D	Senior Product Manager
"On our side, we offer the cloud platform and the tools, the technology so that the customers can build their own solutions themselves and keep control of the related know-how".	Horizontal Integration	Cloud systems	Company D	Senior Product Manager

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Guilherme Brittes Benitez, Ph.D., is an Assistant Professor at the Industrial and Systems Engineering Graduate Program of the Polytechnic School, Pontifical Catholic University of Parana (PUCPR). At PUCPR, he is the Director of the Group on Operations, Products, and Digital Strategies (GOPED – Grupo de Operações, Produtos e Estratégias Digitais). He is also a Research Fellow at the Organizational Engineering Group (NEO – Núcleo de Engenharia Organizacional), Federal University of Rio Grande do Sul (UFRGS), in Brazil. In addition, he has been a visiting scholar at Politecnico di Milano (Italy). He holds a Ph.D. degree in Industrial Engineering from UFRGS. His research is devoted to the interface between operations and technology management with emphasis on digital transformation and Industry 4.0, product and service development, supply chain management, platforms, startups, and innovation ecosystems.

Antonio Ghezzi, PhD, is a Professor of Strategy & Marketing at the Department of Management, Economics and Industrial Engineering – Politecnico di Milano. His main research field is Strategy and Digital Innovation & Transformation, with a focus on digitally-enabled Business Model Design and Innovation. He is author of more than 80 refereed journal articles, books, book chapters and conference proceedings.

Alejandro G. Frank, Ph.D. is an Associate Professor at the Department of Industrial Engineering of the Federal University of Rio Grande do Sul (UFRGS) and the Director of the Organizational Engineering Group. He received Ph.D. (2013) and M.Eng. (2009) degrees in Industrial Engineering from UFRGS, Brazil, and a B.Eng. degree in Industrial Engineering (2007) from the National University of Misiones (UNaM), Argentina. He has been a research affiliate at the Massachusetts Institute of Technology (USA), and visiting researcher at Politecnico di Milano (Italy). His research is devoted to the interface between operations and technology management, with emphasis on digital transformation, Industry 4.0, and new business models in manufacturing firms.