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Designing the future of coopetition: An IIoT approach for empowering SME networks

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Abstract

In an era where Information and Communication Technologies (ICT) redefine the boundaries of competition and collaboration, the concept of coopetition — simultaneous competition and cooperation — emerges as a strategic imperative for small and medium-sized enterprises (SMEs). This study presents the design and development of an Industrial Internet of Things (IIoT) artefact designed to enable competition among SMEs. Bringing the Service-Dominant Logic (S-D logic) foundations to IIoT, a Design Science Research (DSR) approach was employed. This approach facilitated the integration of design theory with practical problem-solving, creating the Coopetition IIoT-based System. The primary goal of this solution is to augment the dynamics of coopetition networks, with a particular focus on SMEs. The practical evaluation of the Coopetition IIoT-based System is assessed through a prototype evaluation by experts representing twenty-four manufacturing stone SMEs, a crucial sector in the Portuguese economy. The feedback received was highly positive, indicating a positive evaluation rate of 78.9%. This favourable response highlights the Coopetition IIoT-based System's proficiency in fostering simultaneous competition and cooperation throughout the lifecycle of business opportunities in SME networks, thereby underscoring its potential as a facilitator of effective competition. Theoretically, this research enriches the application of S-D logic in coopetition networks and advances state-of-the-art IIoT systems. Practically, the Coopetition IIoT-based System demonstrates significant potential in boosting the competitiveness of SMEs in developed economies. Nonetheless, the ultimate efficacy of such IIoT systems will be best determined through real-world application and evaluation. Future research should concentrate on the real-case deployment and assessment of Coopetition IIoT-based Systems within coopetition networks.

Keywords Coopetition · Value Creation · S-D Logic · IIoT · SMEs

1 Introduction

The proliferation of Information and Communication Technologies (ICT) has been a driving force behind process automation, the widening global market, and job access [5]. In response, business activities are increasingly transitioning towards collaborative, knowledge-intensive services that support manufacturing and innovation [61]. This shift has made service innovation a critical priority for nations, businesses, and citizens [3].

Coopetition, the simultaneous blend of competition and collaboration, has become an important topic in contemporary business literature [55]. It is often seen as a strategic approach for small and medium-sized enterprises (SMEs) to survive or access wider market opportunities [15]. Unlike pure collaboration, coopetition involves firms working together while simultaneously competing, which introduces unique challenges and opportunities that require careful management [8]. However, many coopetition networks still need to achieve their intended lifespan [50]. This indicates that the complex balance between competition and collaboration in such networks is difficult to maintain [13]. Furthermore, a review of the current state-of-the-art reveals a lack of adequate technological solutions that significantly mitigate or address this prevalent challenge for SMEs [43].

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This gap in effective solutions underscores a broader issue: a relatively low understanding of networks in coopetition [38].

In modern business, technologies often labelled as 'disruptive'—such as Artificial Intelligence, the Internet of Things (IoT) [10], and cyber-physical production systems—are rapidly evolving [12]. These technologies are transcending their roles as facilitators of human interactions to become active, independent agents capable of deliberate actions [18]. This evolution marks a significant shift in how businesses operate, integrating more sophisticated forms of human capabilities. Given this backdrop, a pressing question arises for SMEs grappling with the challenges of globalization: How can an IIoT system support coopetition networks among SMEs?

This question underscores the need for specialized technologies tailored to the unique demands of coopetition, particularly for SMEs striving to thrive in a globally competitive environment.

The Industrial Internet of Things (IIoT) refers to the extension and application of the IIoT in industrial settings and sectors [34]. While IoT broadly encompasses the interconnectivity of devices and systems through the Internet, IIoT focuses explicitly on integrating smart technologies within industrial processes, manufacturing, and infrastructure [74].

In the context of IIoT, various physical devices, sensors, machines, and other equipment are equipped with embedded technology and connectivity features, allowing them to collect and exchange data [34]. This data is often analyzed to optimize processes, enhance efficiency, and make informed decisions within industrial environments [53]. Key features and components of the Industrial Internet of Things include sensors and actuators, connectivity, data analytics, cloud computing, cyber-physical systems, and security. IIoT represents a transformative approach to industrial processes by leveraging the power of connectivity and data to pursue enhanced productivity and innovation. IIoT can be crucial in coopetition by facilitating real-time data exchange and collaboration while maintaining competitive edges where necessary [21].

From a review of coopetition made by Abhilasha Meena, Sanjay Dhir, and Sushil Sushil (2023), coopetition is mainly addressed through Game Theory, Resource-Based Theory, Paradox Theory, Transaction Cost Theory, and Network Theory [40]. These approaches often narrow their focus on the allocation and use of resources to gain competitive advantages, thereby relegating value co-creation between rivals to a secondary consideration. This rivalry emphasis can limit coopetition's strategic potential, which ideally balances competition with collaboration to maximize mutual benefits [8].

In contrast, the evolving economic landscape toward service economies calls for a broader perspective, as captured by Vargo and Lusch's [69] concept of Service-Dominant Logic (S-D Logic) (Stephen L. [69]). This theoretical framework represents a paradigm shift from the traditional goods-dominant logic, which prioritizes tangible goods exchange, to a perspective that centres service as the core of economic exchange and value creation. S-D Logic provides a holistic, customer-centric approach that emphasizes actor interaction and the ongoing process of value co-creation in today's dynamic and interconnected world [17]. The IoT emerges as a transformative force within this framework, reshaping traditional manufacturing processes and redefining value chains and ecosystems (Stephen L. [68]). This transformation aligns with S-D Logic principles, which focus on value creation within service ecosystems facilitated by actor-generated institutions and arrangements (Stephen L. [71]).

When viewed through the lens of service ecosystems, IIoT systems are recognized as essential enablers in coopetition networks, promoting a harmonious balance between competition and collaboration (S. L. [63]). IIoT can empower SMEs to compete globally while collaborating on innovation, resource sharing, and market expansion [34].

To leverage this potential, the Design Science Research (DSR) provides a framework for developing artefacts [47]. Consequently, this research is dedicated to designing and demonstrating an IIoT system to empower firms to navigate the nuances of coopetition effectively. The goal is to assist firms in managing the entire spectrum of opportunities within these networks, from their initiation to their eventual outcome, whether successful or otherwise.

Building on the DSR framework, the following sections of this paper are structured to guide the reader through the development and demonstration of the Coopetition IIoT system. The following section addresses the theoretical foundation, exploring how S-D Logic is applied within coopetition networks to establish the underlying principles that support the system's design. This is followed by a discussion of the DSR methodology, which outlines the systematic approach to creating the Coopetition IIoT system, emphasizing the principles and steps that informed its development. The paper then transitions into a comprehensive system description, highlighting the key components and functionalities that enable SMEs to navigate the complexities of coopetition. Finally, the demonstration of the Coopetition IIoT system is presented, showcasing its application and assessing its effectiveness in real-world scenarios with SMEs. The paper concludes by summarizing the key findings, discussing their implications, and suggesting directions for future research, thus encapsulating the overall contribution of this study to the field.

2 The theoretical foundation for IIoT systems in coopetition networks

S-D Logic presents a paradigm shift in understanding value creation, moving away from the traditional goods-centric view, where value is embedded in products, to a service-centric perspective, where value is co-created through interactions among actors (Stephen L. [69]). In S-D Logic, value emerges from the dynamic interactions between actors within service ecosystems (M. A. [1]). These actors—whether individuals, organizations, or other entities involved in exchange—engage in reciprocal service provision, applying their competencies, such as skills, knowledge, and resources, to benefit others [73].

Service ecosystems are complex, adaptive systems characterized by interconnected networks of actors who continuously interact, exchange services, and co-create value [17]. In these ecosystems, value is not predefined or fixed but is continually shaped and reshaped through ongoing interactions [49]. The dynamic nature of these ecosystems means that value emerges due to continuous exchanges, heavily influenced by the specific context in which they occur [17].

Institutions and institutional arrangements play a crucial role in coordinating these interactions. In S-D Logic, institutions refer to the formal and informal rules, norms, and practices that govern the behaviour of actors within the ecosystem (S. L. [63]). Institutional arrangements are the specific configurations of these institutions that facilitate the smooth functioning of the service ecosystem. They provide the necessary structure and stability, enabling actors to effectively engage in value co-creation processes [29].

By establishing the boundaries and guidelines for interaction, institutions ensure that exchanges are meaningful. They also ensure that value is co-created in a way that aligns with the goals and expectations of the involved actors (Stephen L. [65]). These institutional frameworks also support the integration of resources—both operant (such as knowledge and skills) and operand (such as physical goods and technology)—which are essential for the co-creation of value (Stephen L. [68]).

In this context, value is understood as a dynamic and emergent phenomenon that cannot be isolated from the interactions and exchanges within the service ecosystem (Stephen L. [67]). The focus shifts from individual transactions to the ongoing relationships and collaborations that form the foundation of these interactions. As actors engage with one another, they co-create value by integrating their resources in contextually meaningful ways within the ecosystem [64].

Through this lens, S-D Logic emphasizes that value is not produced independently by a single entity but is co-created through the collective efforts of multiple actors within an institutionalized framework [17]. This approach shifts the focus from a linear, producer-to-consumer model to a more holistic view of value creation, where all actors within the ecosystem contribute to and benefit from the value created [64].

The progression within S-D Logic towards focusing on service ecosystems has led to a nuanced understanding of network formation. These networks are seen as arising spontaneously from the interactions of socially and economically motivated actors, with their formation being facilitated by a combination of institutional forces and technological advancements [36]. Characterized by adaptive interactions, these emergent networks are driven by the collective goal of creating value, which is pivotal in ensuring the ongoing viability and sustainability of the ecosystem (Stephen L. [70]). This perspective underscores the dynamic and interconnected nature of modern business environments, where the collaborative and organic development of networks forms the backbone of value creation.

2.1 Operand and operant technology

Digitization involves converting analogue information into digital format [11]. Once digitized, information can be efficiently processed, stored, and transmitted using digital circuits, devices, and networks [74]. This transformation is at the heart of digitalization, which encompasses the integration of ICT with products, systems, solutions, and services along the entire value chain, covering the full spectrum of product and service life cycles (I. [45]). Digitization has given rise to digital networks, fundamentally altering traditional notions of place — where tasks are performed and resources are delivered [23]. In the human service activities domain, digitization has led to the adoption of physical tools and forms, enhancing efficiency and enabling the faster, more consistent replication of services [77].

For S-D logic, technology is a resource with a double role in networks [44]. Emphasizing that value is cocreated through the interaction of operant and operand resources for S-D logic. Operand technology refers to the tangible, physical components. In contrast, operant technology involves the knowledge, skills, and services that enhance and apply these physical components to create value in the service exchange [28]. Both operand and operant aspects are essential for understanding how technology contributes to value creation from a service-dominant perspective [58].

Converging to S-D logic foundations and addressable as operant resources [36], digital technologies represent a nonstop state-of-the-art updating, incorporating new improvements continuously and increasingly embedding the capability to take collaborative actions without humans [35] leading to a hyper-connected society and an increasingly

global economy [7]. These collaborative capabilities make technologies like IIoT crucial to enabling modern networks [19]. Moreover, these collaborative actions happen not only among machines (Silva et al., 2016) but also among providers, customers [77] and rivals (coopetitors) [33], from which value creation is created by multiple actors and determined by the beneficiary [26].

2.2 S-D logic, IIoT, and value co-creation

The term "Internet of Things" was first coined by Kevin Ashton, originally from Procter & Gamble, and later associated with MIT's Auto-ID Center in 1998 [4]. Ashton emphasized that, regardless of the specific business proposition, every object could become a part of the Internet [72]. Over two decades since its inception, the capabilities of IoT have significantly expanded. Today, integrating wireless communication, sensors, and computing power is increasingly commonplace in IoT systems [42].

This advancement enables uniquely identifiable objects to transmit data over the Internet autonomously, often with minimal or no human intervention [19]. Additionally, it marks a significant shift in how objects interact and contribute to the digital ecosystem, laying the groundwork for new avenues of value creation in various sectors, particularly in the context of the IIoT [74].

The IoT and embedded systems era, further reinforced by recent technological advancements [48], finds a significant linkage to ecosystems within the S-D logic literature [63]. In these ecosystems, actors are interconnected through various sensors [27], facilitating the location and identification of these actors and enabling their operation innovatively [43]. Empirical studies have shown that IoT-based developments empower companies to offer novel services [42]. These services range from remote control capabilities to predictive maintenance solutions, among others, expanding what companies can offer [39].

Building upon the IoT's foundation, the IIoT is increasingly recognized for elevating efficiency levels in manufacturing SMEs [34]. It is focused on fostering intelligent, self-regulating, and interconnected processes within industrial value creation, thereby enhancing the manufacturing industry's competitiveness [9]. The IIoT amalgamates a diverse array of previously unconnected technologies through today's nearly universal IP-based networks, repurposing them for innovative applications [62].

However, while technologies like Ethernet enable these 'things' to connect, the practical utility of such connections relies on establishing a standard, meaningful communication protocol [25]. This necessity underscores the importance of connectivity and Interoperability in implementing IIoT solutions, ensuring that the various components within these networks can communicate effectively to realize their full potential [74].

In the context of S-D logic, value co-creation, particularly involving customers, is closely linked with the application of operant and operand technologies [63]. The IIoT epitomizes this idea by merging the global outreach of the Internet with industrial capabilities. This integration allows for the control, coordination, and management of the physical world, encompassing goods, machines, factories, and infrastructure (I. [45]).

Aligned with S-D logic's perspective on operant and operand resources (R. [36]), ICT and service management literature [39] (often reference intelligent artefacts or systems. These can execute specific functions autonomously [31] and respond to user interactions based on predefined property sets of objects. However, some scholars argue that this approach is successful in more straightforward scenarios, but it may lead to a lack of creativity in more complex processes. The "in-box thinking" of smart objects, as noted, can potentially stifle creativity [56, 57], and inhibit the flexibility required for firms to adapt in rapidly changing environments [59].

3 Research methodology

This research adopts the DSR methodology, which is dedicated to creating and evaluating artefacts that solve real-world problems while advancing theoretical and practical knowledge [47]. This study uses DSR to develop an IIoT-based system, a technological solution designed to foster coopetition within SMEs' industrial networks.

Problem Identification and Motivation: The initial phase of this research focuses on identifying the need for an improved IIoT system to support coopetition, a dual process of collaboration and competition among SMEs. The research builds upon the state-of-the-art IIoT system currently employed in the stone manufacturing industry [56, 57], recognized for its ability to link processing plants with the cyber market. Despite its effectiveness, the system shows limitations in promoting coopetition, particularly in interoperability, usability, and accessibility (A. Silva, Rabadão, et al., 2020). These shortcomings inhibit the system's ability to facilitate effective collaboration and competition, which creates a compelling motivation for this study's focus on developing an advanced IIoT artefact that addresses these gaps.

Objectives of the Solution: The primary research objective is to create an artefact that enhances the IIoT system by integrating mechanisms designed to promote coopetition within SME networks. This objective is grounded in S-D Logic (Stephen L. [68]), which highlights the importance of value co-creation through resource integration. The goal is to enable the IIoT system to not only bridge gaps in interoperability, usability, and accessibility but also transform how SMEs collaborate and compete. The resulting artefact, referred to as the Coopetition IIoT-based System, is designed to enhance interactions, foster collaboration, and allow businesses to engage in competitive innovation while co-creating value.

Design and Development: The design and development phase focuses on creating specific mechanisms that address the identified gaps. Guided by DSR principles [47], this phase emphasizes the design of innovative solutions that will foster coopetition by enhancing the system's interoperability, usability, and accessibility: (1) Interoperability mechanisms are developed to ensure seamless interactions between different systems and actors within the network. By enabling the efficient exchange of data and resources across various platforms, the Coopetition IIoT-based System fosters collaboration between competitors while maintaining data integrity and compatibility across different technological infrastructures. (2) Usability and accessibility mechanisms simplify the system's interface, making it intuitive and adaptable for SMEs of varying technological capabilities. Accessibility mechanisms are implemented to ensure that all stakeholders can quickly adopt and engage with the system, thus facilitating broad participation within the coopetition network. The development of these mechanisms draws on operand and operant resources [58], ensuring that the system not only processes data but also supports the co-creation of value by allowing businesses to leverage both physical and intellectual assets in a competitive environment. This ensures that the system can facilitate real-time collaboration and competition within a dynamic industrial network [42].

Demonstration: Following the design and development of the Coopetition IIoT-based System, the prototype is demonstrated in a real-world SME context. The demonstration phase is a critical step in the DSR process as it validates the artefact's ability to achieve its intended purpose within an operational environment. The demonstration highlights the system's capacity to enable value co-creation and foster innovation by seamlessly integrating interoperability, usability, and accessibility mechanisms. It illustrates how the system aligns with the objectives set forth at the beginning of the research, providing real-time solutions for enhancing coopetition.

4 Developing a coopetition IIoT-based system

4.1 IIot interoperability mechanisms for coopetition IIoT-based systems

Realizing the full potential of the IoT hinges on establishing global communication standards that meet a range of complex requirements [24]. Converging to S-D logic literature, achieving this vision involves fostering broad Interoperability, which includes shaping laws, regulations, and social norms to support the institutionalization of service ecosystems (S. [64]). As digital service innovation increasingly relies on integrating institutional and technological dimensions, it is crucial to develop network structures that enable this integration (Stephen L. [68]). Furthermore, in addressing interoperability challenges within ecosystems, Akaka and Vargo (2014) emphasize that IoT systems incorporate resource density and digital materiality mechanisms, further strengthening service mechanisms within these ecosystems (M. [2]).

Anchored on this view, systemic Interoperability is required for IIoT systems like Coopetition IIoT-based Systems, ensuring effective collaboration both within and outside the network [32]. Such collaboration should be designed so that mutual goals are achieved, or the network can be controlled in the event of a failure [51].

In this regard, the operant and operand Coopetition IIoT-based System resources must incorporate systemic Interoperability, encompassing (1) Technical Interoperability — establishing technological facilities for reliable communication pathways [76]; (2) semantic Interoperability — ensuring that the exchanged information and message patterns are meaningful and understood across different systems; and (3) pragmatic Interoperability — achieving alignment with the intentions, expectations, business rules, and organizational policies of collaborating parties [52]. Through such systemic Interoperability, the Coopetition IIoT-based System facilitates actors in accessing and sharing essential information, like expectations, business rules, and organizational policies, enhancing collaboration in the network [22].

4.1.1 Resources density mechanisms

The concept of resource density mechanisms, derived from S-D logic literature, plays an essential role in the evolving landscape of the IIoT, particularly in Coopetition IIoT-based Systems. Michel et al. [41] describe resource density as creating optimal resource combinations through dematerialization mechanisms (R. [36]). This process involves

two key dimensions: (1) Liquification — as defined by Lusch and Vargo (2007) and further elaborated by Vargo and Akaka [66], liquefaction refers to the separation of information from its physical form, enhancing its mobility and utility (Stephen L. [66]). In the context of Coopetition IIoT-based System, this translates to the fluid movement and application of data across different nodes of the network, enabling more agile and responsive decision-making processes; unbundleability—this concept, explored by Normann (2001) and further by [41], involves the disentanglement of traditionally fixed activities, allowing them to be more flexibly managed and executed [41]. In Coopetition IIoT-based System, tasks and operations, previously constrained by time and place, can now be dynamically reconfigured, leading to increased efficiency and adaptability in networks.

These mechanisms, liquification and unbundleability, foster the emergence of new resource densities. As [77] suggest, these new densities can be combined innovatively with other actors' resources to create novel value configurations [77]. Crucially, as Ng and Wakenshaw [45] point out, the resource density mechanism in Coopetition IIoT-based System is not just about the physical resources but also encompasses the subsequent processing and analysis of information (I. [45]). This analytical capability is essential for supporting informed decisions and strategic actions, enabling effective coopetition within networks. Coopetition IIoT-based System, by incorporating these principles, demonstrates a shift towards more fluid, adaptable, and collaborative IIoT environments. The system's ability to fluidly reconfigure resources and information enhances operational efficiency and fosters a cooperative yet competitive ecosystem, essential for driving innovation and value creation in the coopetition domain.

4.1.2 Digital materiality mechanisms

The concept of digital materiality emerges as a critical mechanism for enhancing network functionality and value co-creation in IIoT environments. Digital materiality, as defined by [20], centres around the capabilities of physical objects when augmented by software [20]. More specifically, as [75] elucidate, it involves the manipulation of digital representations of physical objects through embedded software, thereby extending and transforming their functionalities [75]. In the case of the Coopetition IIoT-based System, digital materiality is not just a theoretical construct but a practical enabler. By embedding advanced software capabilities into the system, the Coopetition IIoT-based System transcends traditional physical limitations. This integration allows for more dynamic interactions between the digital and physical components of the system. For instance, real-time sensor data can be processed,

analyzed, and used to inform immediate adjustments in machine operations, leading to more efficient and responsive production processes.

Furthermore, this mechanism is crucial in value co-creation within IIoT networks. The enhanced capabilities brought about by digital materiality enable various stakeholders — from manufacturers to end-users — to interact, collaborate, and innovate in ways previously unattainable. For example, the ability to remotely monitor and optimize equipment performance not only improves operational efficiency but also opens new avenues for customer engagement and service innovation. Thus, in a Coopetition IIoT-based System, digital materiality is not merely a feature but a transformative force that redefines the boundaries of what is possible in IIoT environments. It empowers the system to become more than the sum of its physical parts, evolving into an integrated platform where digital intelligence and physical processes coalesce to drive the next wave of industrial innovation.

Building upon these foundational S-D logic concepts, the Coopetition IIoT-based System represents a significant advancement in IIoT. This evolution is exemplified by the transformation of the state-of-the-art "two virtual compartments vehicle", as detailed by Silva, Dionisio, et al. (2020), into a more sophisticated "three-compartment virtual vehicle" (fingerprint4.0+), thereby embedding deeper functionality and versatility into the system [56, 57]. The design of fingerprint4.0+ is composed of three distinct compartments, each serving a unique and vital role in the coopetition network:

- **Descriptive Content Compartment —** dedicated to housing the descriptive content of the product specifications. It represents the collaborative effort between the manufacturer and the customer, embodying the essence of co-creation in product development. This compartment ensures that the final product aligns seamlessly with the customer's needs and expectations.
- **Coopetition Information Compartment —** is a novel addition that carries specific information intended for coopetitors. This includes complementary notes, remarks, and other relevant data facilitating a cooperative yet competitive environment. By sharing selected information with coopetitors, this compartment fosters a culture of shared innovation and improvement, enhancing the overall value of the network.
- **Geometric Information Compartment —** The third and final compartment is a critical component in the manufacturing execution process. It contains the product's geometric information, which generates intelligent objects. These objects are then downloaded and employed in manufacturing, ensuring precision and efficiency in production.

Integrating these three compartments in fingerprint4.0$^+$ signifies a significant leap forward in IIoT state-of-the-art capabilities (A. Silva, Rabadão, et al., 2020). This enhanced structure streamlines the manufacturing process and reinforces the collaborative and competitive dynamics within the coopetition network. By incorporating these advanced mechanisms into the Coopetition IIoT-based System, the system elevates itself from a mere tool to an intelligent facilitator of collaboration and consequent value creation in the industrial landscape, particularly in industrial coopetition networks.

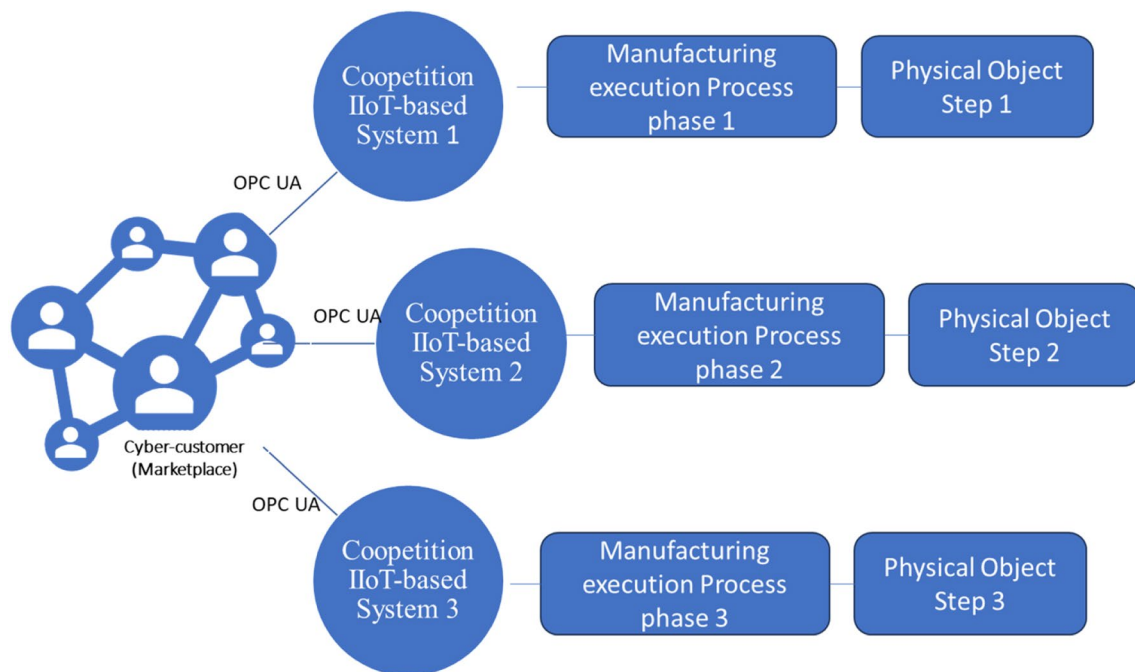### 4.1.3 Embedding interoperability in coopetition IIoT-based systems

Integrating a Service-Oriented Architecture (SOA) in industrial automation systems has been a game-changer since its introduction in 2007 [37]. The Unified Architecture (OPC UA) is at the forefront of this evolution, which offers a scalable, platform-independent solution, fundamentally transforming Interoperability in IIoT systems. As Hoppe [25] noted, OPC UA ingeniously combines the benefits of web services and integrated security within a consistent data model, marking a significant advancement in the field [25].

The Open Platform Communications (OPC) standard, as Lars [30] points out, has been a cornerstone in industrial connectivity, with its adoption spreading across both industrial and non-industrial markets. The transition to a Service-Oriented Architecture with OPC Unified Architecture is fundamental, particularly for systems like Coopetition IIoT-based Systems [30]. This transition aligns with the current technological trends and positions the Coopetition IIoT-based System as a highly interoperable and versatile IIoT system [25].

OPC UA's role in standardizing data connectivity is crucial, as it addresses both horizontal and vertical data communication needs within a network, a point emphasized by [6]. The incorporation of the OPC UA protocol in a Coopetition IIoT-based System enables the system to discover and connect to various OPC UA servers [6], provided the address of the discovery server is known, a functionality underscored by [54]. An illustrative example of horizontal communication is machine-to-machine data exchange on the shop floor [54]. In contrast, vertical communication can be seen in the device-to-cloud data transfer processes. OPC UA is a robust and reliable foundation in both scenarios, facilitating seamless data connectivity and Interoperability within networks [25]. Figure 1 represents this interoperability framework, demonstrating how OPC UA is the backbone for horizontal and vertical communications in Coopetition IIoT-based systems. The figure will illustrate the essential role of OPC UA in ensuring robust, efficient, and secure data exchange across different layers of the IIoT environment in coopetition networks.

The adoption of the OPC UA protocol in a Coopetition IIoT-based System represents a strategic approach to validating and sharing the product's cocreated value proposition. This process is critical not only for ensuring customer satisfaction but also for maintaining transparency and

Fig. 1 Embedding interoperability mechanisms in coopetition IIoT-based System through the OPC-UA protocol

collaboration with all actors involved, including competitors, authorities, and manufacturing process providers.

With the OPC UA protocol, the Coopetition IIoT-based System facilitates a comprehensive validation process. Before finalizing the value proposition, the system makes the enhanced fingerprint4.0 + available to customers and coopetitors. Therefore, fingerprint4.0 + includes detailed information on various aspects of the product, such as its ecological footprint, lifecycle, recycling processes, compliance with regulations, and other relevant data [56, 57]. This level of detail and transparency is crucial in today's market, where ecological and regulatory compliance are as important as the product's functional attributes. Moreover, this transparent approach allows all actors involved in the business opportunity — customers, coopetitors, regulatory authorities, and providers of manufacturing processes — to evaluate and confirm the product's value proposition thoroughly. This collaborative validation process ensures that all parties' needs and expectations are met, fostering trust and cooperation in the network.

Upon receiving confirmation from all involved parties, the Coopetition IIoT-based System takes a pivotal action: It generates and forwards the finalized fingerprint4.0 + to each actor. This fingerprint serves as the blueprint from which intelligent objects are derived for the manufacturing shop floor resources. The transition from a validated value proposition to actual manufacturing execution is seamless, thanks to the robust and interoperable framework provided by the OPC UA protocol within the Coopetition IIoT-based System. In summary, integrating the OPC UA protocol in a Coopetition IIoT-based System is a technological enhancement and a facilitator of collaborative and transparent business practices. By enabling comprehensive validation and information sharing, the Coopetition IIoT-based System aligns with contemporary business paradigms where stakeholder engagement, environmental responsibility, and regulatory compliance are integral to the value-creation process.

4.2 IIoT usability and accessibility mechanisms for coopetition IIoT-based systems

As articulated by Stephen L. Vargo, [71], technological environments must be institutional and systemic, emphasizing that value is cocreated through network actors engaged in resource integration and exchange practices (Stephen L. [71]). It underscores the importance of each actor in providing resources that are accessible and integrable to others, as highlighted by Stephen L. Vargo and Lusch (2008), further underpinning the significance of shared rules, norms, and institutions ([64]).

Rooted in this S-D logic institutional and systemic view, the design and functionality of a Coopetition IIoT-based System must prioritize collaboration among competitors,

ensuring mutual access to resources right from the initial lead moment of an opportunity through its evolution to its culmination, irrespective of whether it results in a win or loss. This approach requires the implementation of robust usability and accessibility mechanisms. These mechanisms are essential in providing secure and efficient access for service exchange among coopetitors. Such facilitation of interactions is crucial in driving value creation within the network (Stephen L. [68]).

To enhance usability and accessibility in these networks, the S-D logic framework highlights the need for institutional and systemic assemblages [23]. Moreover, it calls for developing architectural modules tailored explicitly for transactions and service exchanges (I. [45]). In practical terms, this translates to Coopetition IIoT-based Systems being equipped with modular, adaptable, and user-friendly interfaces and protocols that facilitate transactional efficiency and nurture the systemic integration of services across the network.

Thus, by embracing the S-D logic perspective, the Coopetition IIoT-based System emerges as a technological system and an enabler of a more connected, collaborative, and value-driven IIoT system. By prioritizing usability and accessibility, the Coopetition IIoT-based System fosters a network of seamlessly exchanging resources and services, leading to a richer, more productive, and sustainable industrial landscape.

4.2.1 Systemic assemblage mechanisms

Systemic assemblages are at the heart of understanding how technological resources, like Coopetition IIoT-based Systems, operate and interact within service ecosystems. Systemic assemblages refer to the collective functioning of objects or devices, which can achieve unattainable outcomes by any single component in isolation [16]. They emphasize the emergent capabilities that arise when diverse elements work in unison, transcending the capabilities of individual components (I. [45]).

In service ecosystems, as discussed by S. Vargo & Lusch [64], systemic assemblages can be perceived as structural configurations comprising both the whole and its sub-components. These assemblages, viewed holistically or in segmented forms, represent the intricate interplay of various societal elements (S. [64]). For analytical purposes, examining these assemblages at different levels of aggregation provides valuable insights into how complex systems function and interact.

When applied to the Coopetition IIoT-based System, the principle of systemic assemblages underlines the importance of viewing its usability and accessibility mechanisms as isolated technological features and as a comprehensive collection of heterogeneous technology components. When working in tandem, these components create a synergy that

enhances the system's overall functionality [42]. This interconnectedness is not confined to within-assemblage interactions but extends to between-assemblage communications, enabling Coopetition IIoT-based Systems to integrate and collaborate seamlessly within the ecosystem.

Thus, understanding and optimizing these systemic assemblages in a Coopetition IIoT-based System is crucial for higher usability and accessibility. By ensuring that each technological component performs its function and effectively interacts with other elements, the Coopetition IIoT-based System becomes more than just a sum of its parts. It evolves into a dynamic, responsive, and integrated system capable of adapting and thriving in the ever-changing landscape of industrial automation and IoT.

4.2.2 Architectural modules for transactions and services

Architectural modules in the context of IIoT systems play a pivotal role in redefining how products adapt and respond to varying contexts. As conceptualized by Ng et al. [46], these modules are central to the product's reconfigurability, enabling more personalization and tailoring to specific user needs (Irene [46]). The argument put forward by these authors is that disintermediation and fragmentation of the physical product are not merely structural changes; they are strategic moves that facilitate value creation within ecosystems.

Coopetition IIoT-based System exemplifies the concept of an architectural software module [77], encompassing both operant and operand functionalities, as detailed by Ng & Wakenshaw [45]. This dual functionality allows the Coopetition IIoT-based System to be more than just a rigid, predefined system,it becomes a dynamic, adaptable entity capable of evolving with the needs of its environment.

From this perspective, the usability and accessibility mechanisms within the Coopetition IIoT-based System can be perceived through the lens of architectural modules. These modules are not static entities; they are dynamic, constantly undergoing processes of decomposition and aggregation. As Storbacka et al. [60] highlight, the design process in such a context carefully balances decomposition and aggregation [60]. The goal is to achieve an architectural framework that not only preserves but also enhances a hierarchy of loosely coupled parts. This approach ensures that each component or module within the Coopetition IIoT-based System can function independently yet harmonize effectively with others, providing a flexible and robust structure for transactions and services. In essence, the architectural modules in the Coopetition IIoT-based System are more than mere technical specifications; they represent a design philosophy that prioritizes adaptability, responsiveness, and user-centricity. By adopting this approach, the Coopetition IIoT-based System positions itself as a tool and a facilitator of innovation and value creation in the ever-evolving landscape of industrial IoT.
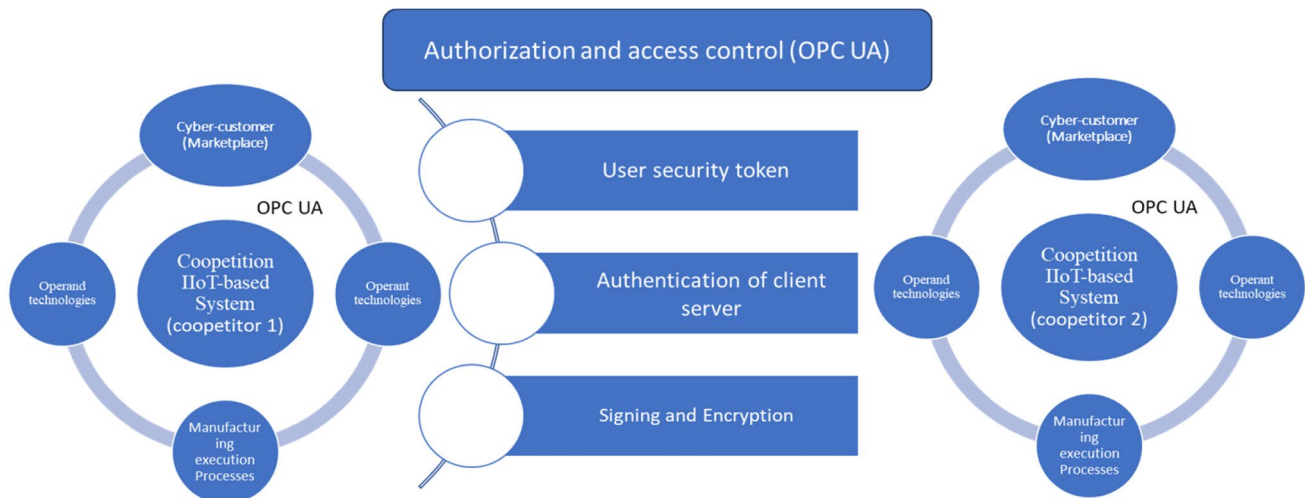
4.2.3 Embedding usability and accessibility mechanisms in coopetition IIoT-based systems

To effectively embed usability and accessibility mechanisms in a Coopetition IIoT-based System, the system leverages the capabilities of the OPC UA protocol, renowned for its foundation in the service-oriented architecture paradigm. This choice is strategic, as OPC UA's design inherently supports the needs of complex IIoT systems. Central to this protocol is its information model, which grants access through services that predefine generic standardized services. Such a setup is crucial in ensuring compatibility across all OPC UA implementations, aligning seamlessly with the interoperability goals of a Coopetition IIoT-based System.

A feature of the OPC UA protocol is its robust security framework. When establishing a session, the OPC UA user security protocol mechanisms come into play, offering tailored security features for diverse environments [25]. This protocol includes exchanging digitally signed certificates during the session setup, a critical OPC UA application security protocol component. These certificates authenticate the entities involved and ensure the integrity and confidentiality of communications. Instance certificates identify specific installations, adding another layer of security. Furthermore, OPC UA transport security protocol mechanisms safeguard data integrity and confidentiality [42]. These mechanisms are adept at preventing message tampering and eavesdropping, ensuring that every communication within the network remains secure and reliable (Fig. 2).

In the context of a coopetition network, these OPC UA mechanisms enable multiple Coopetition IIoT-based Systems to function efficiently on behalf of various coopetitors. This network framework facilitates value co-creation across three critical dimensions: the customers, the rivals', and the providers. These dimensions are integral to the coopetition network, ensuring that collaboration among coopetitors persists throughout the business opportunity, from inception to conclusion, whether it results in a win or loss.

Figure 2 visually represents how OPC UA's security protocols are embedded in the Coopetition IIoT-based System, reinforcing the system's capability to support secure and effective coopetition. By leveraging these sophisticated security and interoperability features of OPC UA, the Coopetition IIoT-based System emerges as a powerful tool in facilitating a secure coopetition environment, essential for driving innovation and value creation in today's dynamic business landscapes.

Fig. 2 Embedding usability and accessibility mechanisms in coopetition IIoT-based systems through the OPC-UA protocol

4.3 The prototype — coopetition IIoT-based system

In line with the DSR approach, this section presents a comprehensive overview of the Coopetition IIoT-based System prototype [47]. From the above sections, this IIoT-based system was designed to integrate SMEs within a coopetition network, leveraging advanced technologies to ensure robust Interoperability, security, and scalability across diverse industrial environments. The system's primary goal is to enable SMEs to effectively balance competitive and collaborative activities, thereby enhancing their ability to co-create value while maintaining a competitive edge. Figure 3 visually represents the prototype's interface, providing a clearer understanding of its functionalities.

Key Components of the Coopetition IIoT-based System Prototype can be summarized:

- The foundation of the Coopetition IIoT-based System is an SOA. This architecture facilitates the modular design of services that can be easily integrated and reused across the network, catering to the dynamic needs of the coopetition network. SOA allows services to be adaptable to various business opportunities and collaborative scenarios, ensuring flexibility and responsiveness within the network.
- At the core of the prototype is the OPC UA protocol. OPC UA provides a scalable, platform-independent framework that ensures Interoperability between different systems and devices within the IIoT environment.
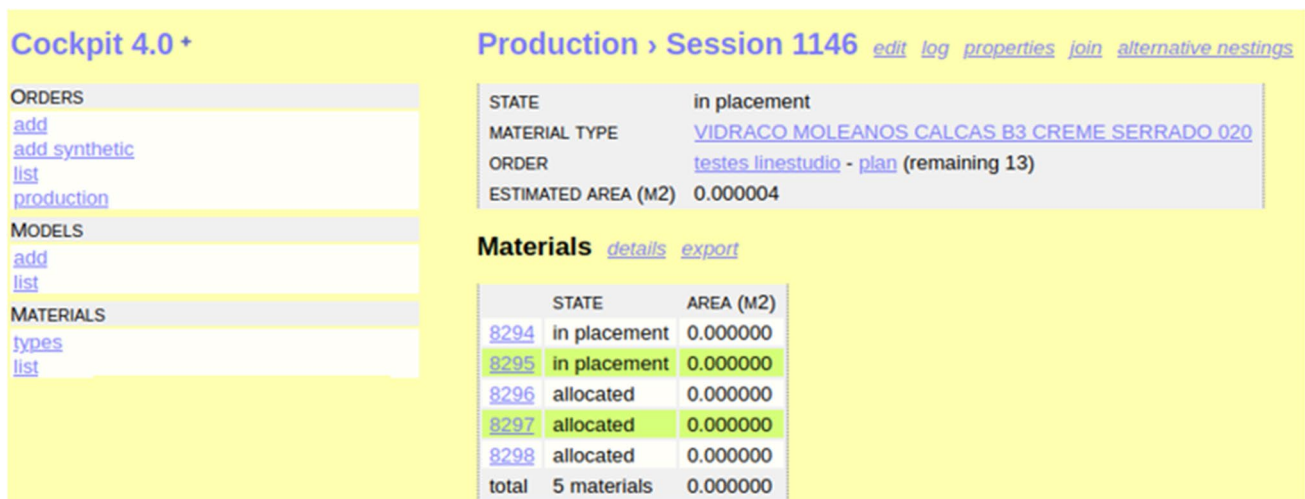
Fig. 3 Visual interface of the coopetition IIoT-based system prototype

The protocol supports horizontal communication (e.g., machine-to-machine interactions on the shop floor) and vertical communication (e.g., device-to-cloud data exchanges), making it a critical component for seamless data integration and interaction within the network.

- A standout feature of the prototype is Fingerprint4.0 + , an advanced tool that captures comprehensive information about each product. This includes details such as the product's ecological footprint, lifecycle, recycling processes, and compliance with regulations. This data is made accessible to all actors within the coopetition network, fostering transparency and enabling collaborative validation of the product's value proposition.
- The security of the Coopetition IIoT-based System is reinforced through the robust mechanisms provided by OPC UA. These include digitally signed certificates, instance certificates, and transport security protocols, which ensure the integrity, confidentiality, and authenticity of communications across the network. This security framework is crucial in a coopetition environment, where sensitive information must be protected against unauthorized access and tampering.

This Coopetition IIoT-based System operates within a network of SMEs engaged in coopetition, where multiple systems collaborate to facilitate value co-creation. The prototype's workflow can be structured as follows:

- The system initiates by discovering and connecting to various OPC UA servers within the network. Once established, this connection enables seamless communication between machines, devices, and cloud services, forming the foundation for subsequent interactions.
- Leveraging the OPC UA protocol, the system facilitates data exchange across different layers of the IIoT environment. This includes horizontal communication (e.g., machine-to-machine on the shop floor) and vertical communication (e.g., device-to-cloud), ensuring comprehensive data integration throughout the network.
- Before finalizing a product's value proposition, the system disseminates the enhanced Fingerprint4.0 + to all relevant actors within the network, including customers, coopetitors, and regulatory authorities. This collaborative validation step thoroughly evaluates the product's attributes, ensuring all parties' needs and expectations are met.
- Upon receiving confirmation from all involved parties, the system generates the finalized Fingerprint4.0 + and distributes it to each actor. This fingerprint serves as the blueprint for the manufacturing process, ensuring that production is aligned with the collaboratively validated value proposition.

- Throughout the entire process, OPC UA's security protocols are actively enforced to safeguard all communications within the coopetition network. This ensures that the network operates in a secure environment, protecting sensitive data and maintaining the integrity of the coopetition activities.

In summary, the Coopetition IIoT-based prototype exemplifies a robust, secure, and adaptable system designed to empower SMEs to navigate the complexities of coopetition networks effectively.

5 Coopetition IIoT-based system prototype demonstration

A comprehensive prototype demonstration was conducted to demonstrate the Coopetition IIoT-based System's effectiveness as a coopetition facilitator within SME networks. This demonstration involved a carefully selected group of experts, each representing one of twenty-four manufacturing stone SMEs—a sector crucial to the Portuguese economy. This sector provides over 16,600 direct jobs in Portugal, significantly contributing to employment in inland regions. Despite ongoing challenges, the sector has seen sustained export growth, positioning Portugal as a leading player in the international ornamental stone market (Agostinho [14]).

The prototype demonstration occurred between October 1st, 2023, and November 1st, 2023, culminating in a comprehensive final session on December 11th, 2023. During multiple sessions, the Coopetition IIoT-based System was evaluated by experts. To tailor the demonstration sessions appropriately, each SME's digital maturity level was assessed. The digital maturity levels were categorized as follows:

- DL#0: No digital tools are used.
- DL#1: At least one computerized machine on the manufacturing shop floor.
- DL#2: All machines are computerized.
- DL#3: All machines are computerized and connected to the ERP system.
- DL#4: All machines are connected to the ERP system and can interface with Building Information Modelling (BIM) architects' stations.

This approach ensured a diverse representation across various stages of digital readiness, providing valuable insights into how the Coopetition IIoT-based System's functionalities were perceived by the SMEs involved. The demonstration process included four key actions:

- Introduction: The session began by highlighting the shift towards BIM and the upcoming need for stone companies to adapt to BIM-shaped procurement in the Architecture, Engineering, and Construction (AEC) market. A tangible demonstration of the Coopetition IIoT-based System interface complemented this introduction.
- Explanation: This phase involved a detailed explanation of the Coopetition IIoT-based System's functionalities, focusing on innovation, usefulness, cybersecurity, and usability in facilitating coopetition among rival SMEs. Key features discussed included resource sharing without prior partner knowledge, maintaining commercial confidentiality, and automated resource allocation based on buyer decisions.
- Evaluation: Experts were asked to rate the system on a scale of one to five across several performance metrics:

  o System Usability: The ease with which SMEs could integrate and utilize the system within their operations.
  o System Interoperability: The system can seamlessly connect with various devices and platforms across digital maturity levels.

  o System Cybersecurity: The effectiveness of the system's security protocols in protecting sensitive information during coopetition activities.
  o System Scalability: The system's ability to adapt and scale as the needs of the SMEs and the complexity of their operations grow.

- Data Collection: Quantitative ratings were collected, anonymized to maintain confidentiality, and documented for analysis.

Table 1 presents the respondents' ratings of the Coopetition IIoT-based System functionalities across different digital maturity levels. The data indicate that DL#0 respondents rated the system's Interoperability low at 1.2, reflecting their limited digital integration. In contrast, DL#4 respondents, representing the most digitally advanced companies, rated Interoperability at a maximum of 5 out of 5, highlighting its importance. Scalability also received high ratings, particularly from DL#4 respondents, who rated it 5. Even DL#0 respondents acknowledged the system's scalability, giving it a score of 4.

Table 1 Respondent's ratings of coopetition IIoT-based system functionalities

Evaluation of the IIoT-based system	Usability	Interoperability	Cybersecurity	Scalability	Average evaluation
DL#0 Respondents	4.3	1.2	2.6	4.0	3.0
DL#1 Respondents	4.7	2.3	3.8	4.2	3.8
DL#2 Respondents	4.9	3.1	3.0	4.2	3.8
DL#3 Respondents	5.0	4.6	3.0	4.9	4.4
DL#4 Respondents	4.9	5.0	4.1	5.0	4.8
Average rating	4.8	3.2	3.3	4.5	3.9

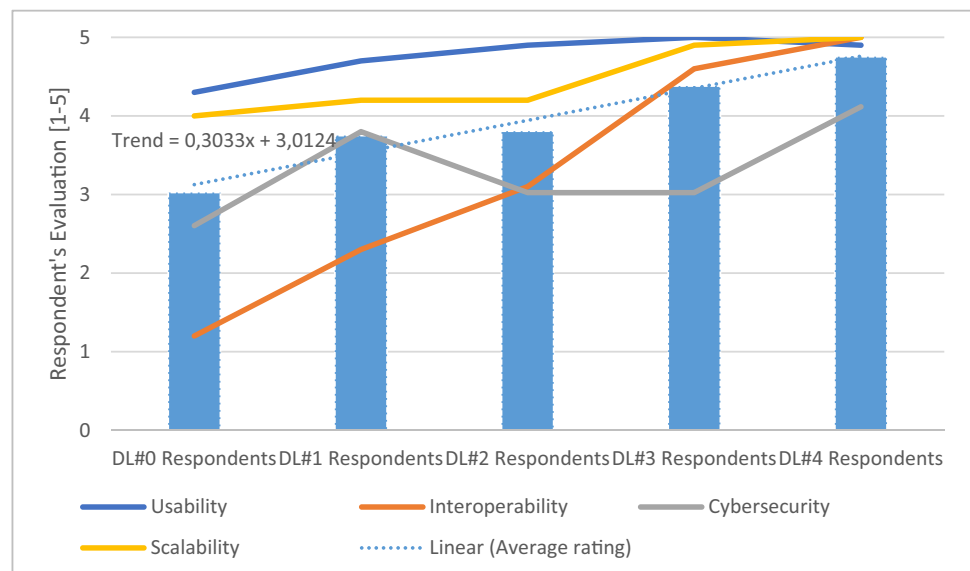**Fig. 4** Evaluation of the coopetition IIoT-based system functionalities

Figure 4 visually represents the evaluation of the Coopetition IIoT-based System functionalities by SME representatives, further illustrating the positive reception and identifying areas for improvement. As digital maturity increases, respondents evaluate the system's functionalities more positively, as indicated by a positive trend with an average increase of 0.3033. This trend likely reflects the greater appreciation of digital technologies' advantages among more digitally advanced companies.

The aggregated evaluation ratings from the demonstration highlighted the perceived innovation of the Coopetition IIoT-based System, with an impressive average score of 3.9 out of 5. This score suggests the prototype's potential functional efficacy within the sector. The system's usefulness was positively correlated with the companies' digital maturity, with the most digitally advanced respondents (DL#4) giving high scores, averaging 4.8 out of 5.

While cybersecurity emerged as an area needing improvement, with an average rating of 3.3 out of 5, the prototype demonstrated significant promise as a tool for enabling coopetition, particularly among SMEs with higher digital levels. The feedback underscored the exceptional value of the system for entities at the forefront of digital integration. However, given the identified cybersecurity concerns, a focused review and enhancement of the system's security features are advisable. Strengthening these aspects will bolster confidence in the prototype and enhance its overall utility and acceptance among SMEs.

The Coopetition IIoT-based System achieved a positive evaluation rate of 78.9%, underscoring its potential as a transformative tool for SMEs. The system's ability to balance competition and collaboration among SMEs was particularly noted as a key strength, making it a promising solution for fostering innovation and value co-creation in the industrial sector. While the feedback was highly encouraging—especially regarding innovation and usefulness for companies at higher digital levels (DL#3 and DL#4)—the moderate rating for cybersecurity suggests the need for enhanced security measures before practical implementation. Addressing these concerns will ensure the system's success and widespread adoption.

6 Conclusions

This research sought to answer how an IIoT system can support coopetition networks among SMEs. In response, the study developed and demonstrated an IIoT system specifically designed to enhance the dynamics of coopetition—where competition and collaboration co-occur—within SME networks. By grounding the system in S-D Logic and employing the DSR methodology, the research aimed to create a framework beyond traditional technological solutions, offering a robust, knowledge-based platform that supports SMEs in navigating the complexities of global markets through a balanced approach to competition and collaboration.

The Coopetition IIoT-based System developed in this study represents a significant advancement toward achieving this goal. The system's design, which aligns closely with S-D Logic principles, underscores the central role of service in economic exchange and value creation, particularly within the industrial sector. By facilitating real-time data exchange, resource sharing, and collaborative decision-making, the system enables SMEs to balance competitive and cooperative activities effectively, thereby maximizing mutual benefits within coopetition networks.

The practical evaluation of the Coopetition IIoT-based System through a prototype demonstration involving experts from the Portuguese manufacturing stone sector resulted in a positive reception, with a positive evaluation rate of 78.9%. This feedback highlights the system's potential to significantly impact how SMEs engage in coopetition. It gives them a powerful tool to manage the entire spectrum of business opportunities—from initiation to conclusion—while maintaining a balance between competition and collaboration.

The study also contributes to the theoretical understanding of service ecosystems and the application of S-D Logic in modern business environments. By illustrating how IIoT can be harnessed to support coopetition networks, this research advances the discourse on integrating disruptive technologies within traditional manufacturing and service processes, offering a more nuanced approach to competition and collaboration among SMEs.

Looking forward, the research emphasizes the importance of further investigations into the practical application and continuous evaluation of the Coopetition IIoT-based System. Such future research is crucial for validating the current findings and exploring the practical challenges and opportunities that IIoT systems present in real-world coopetition networks. By continuing to refine and enhance these technologies, the research community can contribute to SMEs' sustained competitiveness and growth in the global economy.

Declarations

Conflict of interest The authors declare no competing interests.

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