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Co-Opetition and the Industrial Internet of Things: A Strategic Framework for Operational Efficiency in the Portuguese Ornamental Stone Sector

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Abstract: In our rapidly globalizing and digitizing world, small and medium-sized manufacturing enterprises (SMEs) face significant challenges that compel them to adopt a co-opetition strategy—a blend of competition and collaboration. Despite their potential benefits, the high failure rates and unmet expectations of co-opetition networks highlight a significant gap in the empirical frameworks for establishing and maintaining these networks. This research seeks to address these gaps by developing a framework that enhances value cocreation in the Portuguese ornamental stone sector, integrating the latest developments in the Industrial Internet of Things (IIoT), Service-Dominant Logic (S-D Logic), and service science. Question: How can a framework integrating IIoT, S-D Logic, and service science enhance value cocreation and manage co-opetition among SMEs in the Portuguese ornamental stone sector? Methods: Theoretical insights and practical applications were synthesized to develop and validate a comprehensive co-opetition framework. This framework was tested through an experimental pilot project in the Portuguese ornamental stone sector, leveraging IIoT. Results: The implementation of the framework demonstrated significant operational efficiency, including enhanced performance, reduced production variance, and better resource utilization, indicating that integrating IIoT within co-opetition networks can effectively support SMEs. Conclusions: This study confirms the transformative impact of embedding IIoT in co-opetition networks, offering a replicable and scalable framework for other sectors. This framework addresses the empirical gap and aligns with broader socio-economic goals, setting the stage for further research into its applicability and potential across diverse industrial environments.

Keywords: co-opetition; S-D Logic; service science; IIoT; ornamental stone sector

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1. Introduction

In the contemporary landscape of rapid globalization and digitization, small and medium-sized manufacturing enterprises (SMEs) face unparalleled challenges (Di Bella et al. 2023). These challenges necessitate adopting a co-opetition strategy among firms (Ramírez-López et al. 2021). Co-opetition is praised for its ability to spur innovation and value creation, which are vital for SMEs grappling with issues related to scale, efficiency (Chen 2020), and limited resources for innovation (Bicen et al. 2021). Despite these theoretical benefits, high failure rates and unmet expectations have emerged in co-opetition networks, highlighting a significant gap in empirical frameworks for establishing and maintaining these networks (Crick 2019). This gap is especially critical considering the essential role of manufacturing SMEs in the economies of developed nations (Muller et al. 2021).

The prevailing academic discourse on co-opetition primarily explores competitive dynamics (Kwon et al. 2020) and the resource-based view (Gernsheimer et al. 2021), focusing on structural strategies and securing unique resources for competitive advantage (Rouyre et al. 2024). However, these perspectives often neglect the value creation and sharing mechanisms within co-opetition (Xie et al. 2023). Moreover, they need to adequately address the complexities and evolving nature of co-opetition in the digital era, particularly the significant impact of technological advancements on network interactions (Corbo et al. 2023). The high failure rates of co-opetition networks among SMEs (Reeves et al. 2019) and the insufficiency of current empirical models to navigate the challenges posed by technological progress and the need for digital collaboration underscore this critical research gap.

Technological advancements have reshaped the co-opetition landscape, altering network interactions and emphasizing technology's role as a resource within these networks (Bouncken et al. 2024). In this context, the literature on Service-Dominant Logic (S-D Logic) provides an alternative perspective for understanding value cocreation in networks, where technology acts as both a facilitator and a resource in service ecosystems (Vargo et al. 2024). Grounded in S-D Logic, Maglio and Spohrer (2008) pioneered the reevaluation of value cocreation, shifting from isolated, localized processes to a global network that leverages technology (Demirkan and Spohrer 2018). This led to the establishment of service science as a discipline focused on analyzing service systems as abstract entities, exploring the mechanisms of service innovation within economic activities (Yun et al. 2023; Breidbach and Maglio 2015). How can a framework that integrates technology, S-D Logic, and service science enhance value cocreation and manage co-opetition among SMEs in the Portuguese ornamental stone sector?

To address this question, this research study aims to develop and validate a comprehensive framework for co-opetition networks. This framework is designed to enhance value cocreation in the Portuguese ornamental stone (OS-PT) sector, with a focus on improving manufacturing efficiency and contributing to Sustainable Development Goals (SDGs) (UN 2019). By synthesizing theoretical insights with practical applications, the framework aims to establish a new paradigm at the intersection of the Industrial Internet of Things (IIoT) (Liu et al. 2024), S-D Logic, and service science.

The current relevance of the IIoT lies in its ability to revolutionize industrial processes by enabling unprecedented levels of connectivity (Yazdinejad et al. 2023a), real-time data processing, and intelligent automation. These advancements are particularly crucial for industries facing complex digital and global procurement challenges, such as those introduced by Building Information Modelling (BIM) in the Architecture, Engineering, and Construction (AEC) industry (Hadavi and Alizadehsalehi 2024). The OS-PT sector, with its unique combination of traditional craftsmanship and modern technological demands, presents an ideal context for exploring the potential of co-opetition networks for value cocreation (Silva and Cardoso 2023).

Based on insights from IoT-related cases in the literature (Brewster et al. 2017; Dospinescu and Dospinescu 2018), this study hypothesizes that a co-opetition framework integrating the IIoT with S-D Logic and service science principles will enhance value cocreation and effectively manage co-opetition among SMEs in the OS-PT sector.

2. Literature Review

Central to the S-D Logic introduced by Vargo and Lusch (2004) is the notion that service—the application of competencies for the benefit of others—is fundamental to value cocreation with beneficiaries (Lusch and Vargo 2007). This value cocreation process is intricately facilitated and bounded by institutional frameworks and arrangements, which serve as essential mechanisms within ecosystems (Vargo and Lusch 2016). Despite its controversies (Campbell et al. 2013), the adoption of S-D Logic has significantly influenced the dialogue around business models since 2004 (Vargo and Lusch 2004), providing a coherent framework that has seen notable progress and contributions to service-centric business models over the past decade (Vargo and Lusch 2004). Advancements in S-D Logic further articulate value cocreation in service ecosystems (Lusch et al. 2016). Coordinated by institutions and institutional arrangements, this concept transcends beyond mere tangible resources to include intangible assets and institutional structures (Vargo et al. 2024).

In response to the transition towards service-oriented models, Maglio and Spohrer (2008) advocated for a shift from isolated, localized processes to a globally interconnected network facilitated by technology (Maglio and Spohrer 2008), culminating in the establishment of service science with a focus on exploring the concept of service systems (Demirkan and Spohrer 2018). Central to service science is the notion that any interaction between entities inherently represents an opportunity for cocreating value. This perspective has significantly influenced the development of business models, emphasizing the importance of value proposition design and systemic patterns (Maglio et al. 2009).

Central to service science is the service system concept, encompassing configurations of people, technologies, organizations, and shared information. These systems can create and deliver value through service to various stakeholders, including suppliers, users, and other entities (Maglio et al. 2010). Despite slight differences in terminology from S-D Logic, service science shares a similar nature, embodying distinctive and connective roles within ecosystems and networks, facilitating resource reconfiguration and interaction (Cellary et al. 2019).

The discourse within the literature on service science increasingly focuses on networks of service systems, where multiple actors collaborate to cocreate mutual value. This perspective aligns with the S-D Logic view of networks as adaptive ecosystems for value creation and sustainability (Akaka et al. 2023).

S-D Logic and service science communities emerge as natural allies, sharing overlapping research interests, perspectives, and foundational philosophies (Lusch and Nambisan 2015). Both fields advocate for a holistic approach to studying and scaling business activities, transcending the distinction between tangible and intangible assets by integrating knowledge from diverse disciplines (Cellary et al. 2019). Despite some discrepancies in vocabulary, these communities converge on a shared philosophical view that emphasizes the importance of context in the cocreation of value, a complex phenomenon arising from service exchange, resource integration, and value-in-context, thereby providing a robust foundation for the design of empirical models (Pohlmann and Kaartemo 2017).

3. Technology Innovation for Value Creation

Degani et al. (2017) conceptualize technology through the lens of the "operant" adjective, defining it as "something that works" or is "engaged in action". This perspective delineates technology as a resource capable of self-governance, autonomy, and independence from external control, spanning three distinct logics: (1) authority to create and apply its own rules, (2) self-sufficiency without external assistance, and (3) freedom from external influence (Degani et al. 2017). This framework aligns with the emergence of intelligent technologies that can autonomously generate algorithms and undertake initiatives without human intervention, marking a significant leap in technological capabilities (Bodkhe et al. 2020).

The integration of technology as a central resource for innovation is extensively highlighted within service science, underscoring the transformative impact of technological advancements on service provision, revolutionizing how services are delivered, innovated, and managed (Breidbach and Maglio 2015). Parallel to this, S-D Logic explores the influence of technology on service innovation and the cocreation of value within service ecosystems, acknowledging technology's dual role as both an enabler and a driver of innovation (Matthies et al. 2016; Akaka et al. 2023).

Continuing along the same vein, the literature on co-opetition acknowledges the importance of technology-based strategic networks in fostering collective understanding and collaboration among diverse stakeholders (Doganova and Eyquem-Renault 2009; Rusko 2014; Wang and Chen 2022). This viewpoint is in harmony with S-D Logic and service science, which regard technology as a crucial operand (enabler) and operant (initiator) resource in the value creation process (Matzner et al. 2018; Barile et al. 2019). The interplay between operant and operand resources is facilitated through human interaction, technology, value propositions, and shared information, laying the groundwork for innovation and value creation (Matthies et al. 2016).

In this context, emergent and embedded technologies like the Internet of Things (IoT) are recognized by S-D Logic (Vargo et al. 2024) and service science (Akaka et al. 2023) as heralding a new era in which technology profoundly influences ecosystems. Empirical evidence underscores the transformative potential of IoT-based innovations in fostering novel service offerings (Akaka et al. 2015).

Companies leveraging IoT capabilities can extend their service portfolio to include remote control options and predictive maintenance solutions (Mosch et al. 2023), advancing operational efficiency and opening new avenues for value cocreation within co-opetition frameworks (Salih et al. 2022). This technological integration catalyzes the development of ecosystems where companies, by harnessing IoT, transcend traditional competitive boundaries (Coelho et al. 2022), facilitating the seamless exchange of resources and collaboration among once-competing entities (Mosch et al. 2023).

The IIoT advancement beyond IoT frameworks marks a significant evolution in industries' operations. According to Yazdinejad et al. (2023b), the IIoT introduces unprecedented efficiency and intelligence, enhancing global connectivity and enabling direct device-to-device communications (Yazdinejad et al. 2023b). It facilitates the development of intelligent artefacts capable of dynamically adapting to user interactions and actively enhancing value-creation processes (Hoppe 2023). Furthermore, the implementation of advanced technological frameworks for prognostic health management, for instance, demonstrates the critical role of the IIoT in improving long-term prediction accuracy and operational efficiency in industrial applications (Li et al. 2024). Additionally, the integration of edge computing within IIoT systems has revolutionized industrial processes by providing flexible data sensing and real-time processing services, ensuring efficient resource sharing and maximizing social welfare in edge-enabled IIoT environments (Liu et al. 2024).

To address the research question, the following hypothesis can be formulated: a co-opetition framework that integrates the IIoT with S-D Logic and service science principles enhances value cocreation and effectively manages co-opetition among SMEs in the OS-PT sector. This integrated framework is expected to improve operational efficiency, fostering a collaborative industrial ecosystem that supports sustainable industrialization and contributes to achieving relevant SDGs.

4. Designing a Co-Opetition-Centric Framework for Value Cocreation

4.1. The Role of Technology in Networks for Value Cocreation

Technology plays a central role in co-opetition networks as an initiator and facilitator of actions among actors (Elo et al. 2024). Providers, driven by the prospect of heightened benefits, may share and integrate their resources with others, including competitors, to partake in service exchanges that enrich resource density and enhance value cocreation (Lusch and Nambisan 2015). This collaborative yet competitive approach necessitates the mutual provision of access to resources, fostering a business model predicated on co-opetition (Seepana et al. 2020).

According to this view, technology stands out as a critical element, acting as both an operant resource by initiating actions and an operand resource by facilitating actions (Akaka et al. 2023). Its integration into the network amplifies resource density, propelling value and developing innovative resources designed to enhance the quality of life for all network actors (Vargo et al. 2024). Technology's unique combination and application in co-opetition networks underlines its essential role in advancing competitive collaboration for mutual and ecosystem-wide benefits (Elo et al. 2024).

4.2. The Role of Entities and Resources in Co-Opetition Networks

Understanding the dynamics of co-opetition networks necessitates identifying the roles played by various actors (service systems) and the resources they leverage for mutual benefit. Drawing from S-D Logic, the essence is recognized that of these networks lies in the service exchange among entities, aimed at reciprocal benefits (Barile et al. 2016). This exchange centers on two primary resource types: operant resources (people and organizations with the capacity to act) and operand resources (tangible assets such as technologies and knowledge). The distinction underscores that service is not merely an offering but the application of competencies for another's benefit (Joiner and Lusch 2016).

With its interdisciplinary approach, service science seeks to unify the concept of resources, asserting that anything named and potentially valuable—be it physical or non-physical—constitutes a resource (Vargo and Akaka 2009). These resources are characterized by their lifecycle (beginning, middle, and end), availability, creation cost, maintenance expense, and the cost of ceasing access or use.

The dynamic interplay of these resources within co-operation networks, spanning individuals, technology, organizations, and shared information, catalyzes actions fundamental to the network's vitality (Vargo et al. 2023a). Actors strategically integrate these resources to foster innovation and create value across various levels within the network (Vargo et al. 2023a).

This perspective suggests that all actors within the network are value cocreators (Silva and Gil 2020). Customers assume the pivotal role of evaluators, assessing offerings based on their experiences, while providers act as facilitators of value cocreation (Elo et al. 2024). Co-opetitors contribute through resource sharing (Bicen et al. 2021), competitors function as independent entities competing for customer attention (Akaka and Vargo 2014), and authorities serve as regulatory bodies ensuring sustainable and equitable interactions within the network (Vargo and Lusch 2016).

Revenue expectations within these networks enabled by technology are shaped by value propositions, which, in turn, are driven by the perceived value and the cocreation process. This cyclical engagement fosters increased resource density, propelling the network towards innovative value propositions and enhanced cocreation opportunities (Ng and Wakenshaw 2017). However, the success of this model hinges on the seamless access to and sharing of resources among entities, with the understanding that value perception is inherently subjective and rooted in individual experiences (Akaka et al. 2013).

Upon joining a co-opetition network, an actor anticipates revenue generation, with the process delineated by S-D Logic's service ecosystem view (Vargo et al. 2023b): initial expectations fuel the creation of value propositions, which in turn generate revenue, spurring further value propositions and enhancing resource density for more significant cocreation opportunities (Vargo et al. 2020). This cycle necessitates mutual access to resources among entities, with the proposition's value uniquely shaped by each beneficiary's experience (Jaakkola et al. 2024).

4.3. Institutionalizing Co-Opetition Networks for Value Cocreation

By adopting S-D Logic's view on service ecosystems, in networks, all actors integrate the resources in value networks (Lusch et al. 2010), understood as architectures of service and information flow frameworks (Zott and Amit 2008) where actors have roles, potential benefits, and sources of revenues, leading to business models (Zott et al. 2011).

Drawing from these foundational concepts, value creation transcends simple bilateral exchanges, necessitating a more comprehensive array of resources and the involvement of multiple actors within an intricate network (Normann and Ramirez 1993). The notion of micro-exchange within these vast ecosystems suggests that customers and providers represent just a fraction of the entire network, including numerous actors engaging in reciprocal resource exchange to create value (Chandler and Vargo 2011). Such complex dynamics require a level of coordination facilitated by endogenously created institutions—comprising rules, norms, symbols, and practices that aid collaboration—and institutional arrangements (Elo et al. 2024), which are interdependent collections of these institutions, manifesting even at a societal scale (Meynhardt et al. 2016).

In such institutional technology-enabled networks, actors, including competitors, might choose to collaborate for mutual benefits, showcasing the voluntary nature of co-operation even among rivals (Chandler and Vargo 2011; Vargo et al. 2024). The deployment of both operant and operand technologies facilitates this co-operation through resource liquefaction and enhanced resource density, further cementing the institutionalization of networks into fully fledged service ecosystems (Lusch and Nambisan 2015; Jaakkola et al. 2024).

5. Operationalizing Co-Opetition Networks for Value Cocreation

The evolution of the IIoT brings connectivity and enables direct device-to-device communications (Dospinescu and Dospinescu 2018). This development supports creating intelligent systems that dynamically adapt to user interactions, enhancing value creation processes (Yazdinejad et al. 2023b).

5.1. Systemic Interoperability in IIoT-Based Co-Opetition Networkss

Interoperability is fundamental to fostering effective collaboration within networks, facilitating the achievement of mutual goals or enabling the controlled dissolution of co-operation in case of faults (Hoppe 2023). In the context of co-opetition for value cocreation, exchanging information between operand and operant technology resources is crucial (O'Brien 2016). It necessitates that any artefact designed to enable co-opetition within networks embeds mechanisms to address interoperability, especially within IoT- or IIoT-based systems, focusing on semantic and pragmatic issues to ensure network capabilities are fully leveraged (Leal et al. 2019).

As service science highlights, semantic interoperability ensures that the meaning of exchanged information is understood across different systems, while pragmatic interoperability effectively uses this information in operational contexts (Cardoso et al. 2015). Addressing these interoperability dimensions within IIoT artefacts is vital for enabling the seamless integration of diverse technologies and facilitating collaborative environments conducive to co-opetition (Silva et al. 2016).

Akaka and Vargo (2014) highlight the importance of embedded interoperability in digital technologies to connect network resources, emphasizing specific mechanisms necessary to enhance interoperability (Brewster et al. 2017). They underscore the significance of systemic embedded interoperability within digital technologies for connecting network resources and emphasize specific mechanisms for enhancing interoperability (Akaka and Vargo 2014).

Resource density mechanisms: These mechanisms involve the processing and analyzing of information to support decision-making and action-taking processes. By enhancing the density of available resources, IIoT can offer more nuanced insights and foster more informed co-opetition strategies (Ng and Wakenshaw 2017).

Digital materiality mechanisms: This refers to the capacity of software embedded in physical objects to manipulate digital representations, thereby enabling new functionalities and interactions. Digital materiality bridges the gap between the physical and digital realms, opening up new avenues for innovation and collaboration within co-opetition networks (Maglio et al. 2019).

By incorporating these mechanisms, IIoT artefacts can facilitate the dynamic exchange of service information, creating an environment conducive to collaborative and competitive interactions. Enhancing interoperability co-opetition within networks enables quicker responses to necessary adaptations, ultimately harnessing the full potential of value cocreation.

5.2. Systemic Usability and Accessibility in IIoT-Based Co-Opetition Networks

Usability and accessibility within co-opetition networks are paramount, guaranteeing secure service exchange among competitors and leveraging interactions to enhance value creation within the ecosystem (Kahkonen and Lintukangas 2012). As the S-D Logic literature emphasizes, facilitating these aspects necessitates a systemic perspective on assemblages and architectural modules designed for service interaction (Vargo and Lusch 2016). Institutions and institutional arrangements facilitate this coordination (Elo et al. 2024).

The integration of an IIoT system, encompassing both operant (e.g., artificial intelligence or cognitive assistant modules) and operand modules, allows competitors within the network to engage in activities while lacking legal accountability due to the absence of rights and duties (Maglio et al. 2009). Consequently, it cannot be recognized as a service system within service science (Maglio et al. 2019).

To bridge this gap, the system must incorporate human resources capable of operating, interacting, and collaborating with operant and operand technologies. Within this collaborative team, a designated responsible individual serves as the legal and operational representative of the network actors, ensuring accountability and oversight (Ng and Wakenshaw 2017).

Figure 1 illustrates the principles of the IIoT artefact, embedding mechanisms for systemic interoperability, usability, and accessibility to facilitate co-opetition and value cocreation within networks.

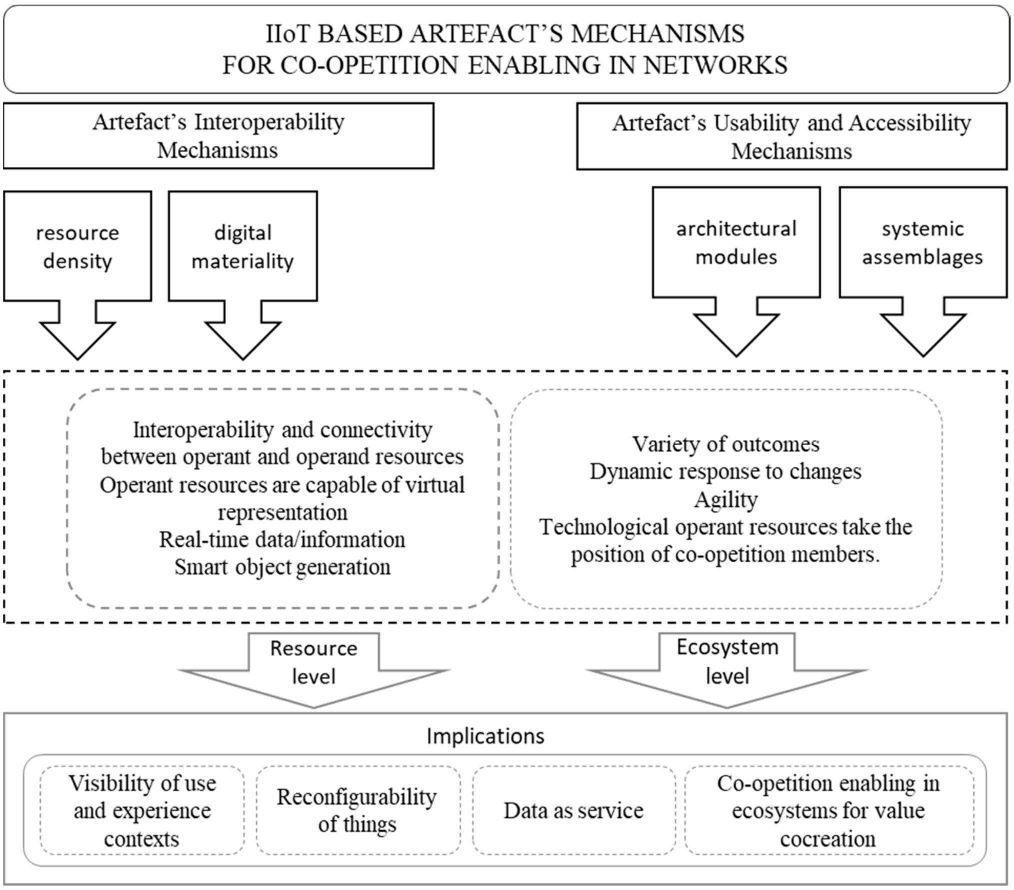

Figure 1. IIoT artifact principles for enabling co-opetition and value cocreation in networks (Ng and Wakenshaw 2017).

This IIoT system categorizes two types of resources critical for its operation: physical and non-physical resources. The category of physical-with-rights resources includes human resources, providing necessary oversight, decision-making capabilities, and legal accountability in network interactions. Non-physical-with-no-rights resources are operand and operant software that facilitate digital interactions and processes.

By equipping the system with these diverse resource types, co-opetition networks for value cocreation can effectively manage usability and accessibility, fostering secure and productive service exchanges. This approach enhances the potential for value creation within the ecosystem. It addresses the legal and operational challenges of integrating advanced technologies like IoT into co-opetition strategies.

6. Evaluating Co-Opetition Networks for Value Cocreation

An experimental pilot project was conducted within the Portuguese ornamental stone sector to evaluate the effectiveness of the proposed framework. The objective was to assess the impact of the co-opetition network and IIoT artifacts on operational efficiency and value cocreation among SMEs. This case study focused on a representative sample of SMEs in the Portuguese ornamental stone sector, an industry characterized by traditional practices and significant potential for digital transformation.

6.1. The Portuguese Ornamental Stone Sector

The Portuguese ornamental stone sector, integral to Portugal's cultural heritage and a symbol of innovative excellence, has contributed to globally renowned stone monuments since the 15th century (Machado et al. 2021). According to recent statistics, the sector boasts a significant economic impact, exporting to 116 countries, ranking as the ninth largest entity in the global stone trade, and holding second place in per capita international trade (Silva and Pata 2022). The industry's exports exceed its imports by 660%, generating a turnover of EUR 1.230 million and sustaining over 16,600 direct jobs, notably supporting employment in inland regions (Machado et al. 2021). Known for its adaptability and resilience, the OS-PT sector has become a formidable industrial force within the country (Silva and Gil 2020). However, it faces significant challenges due to digital and global procurement processes introduced by BIM within the AEC industry, particularly impacting efficiency (Silva and Cardoso 2023).

Innovative technologies developed under the scope of the Inovstone4.0 R&D Project (Silva et al. 2020) exemplify the practical application of the IIoT in the OS-PT sector. This system has notably transformed the connectivity of OS-PT SMEs with the AEC digital market. Brewster et al. (2017) highlighted the application of IoT technologies in agriculture, demonstrating their potential to drive innovation and efficiency in traditional industries (Brewster et al. 2017). Similarly, Dospinescu and Dospinescu (2018) emphasized the role of information technology in enhancing ethical practices and operational efficiency (Dospinescu and Dospinescu 2018). To effectively support co-opetition among firms, a new IIoT artifact needed to be developed, embedding advanced mechanisms for interoperability, usability, and accessibility to integrate the OS-PT sector into a co-opetition network. Although the technical specifics of this new artifact are beyond the scope of this research, these developments culminated in the creation of Cockpit4.0+. This IIoT-based artifact was engineered to facilitate secure interactions among competing firms within the OS-PT sector.

Consequently, Cockpit4.0+ was utilized to connect three competitor firms in a Co-opetition Network Experimental Pilot Project (CN-EPP). As illustrated in Figure 2, the CN-EPP fostered a collaborative industrial atmosphere among these OS-PT competitor firms, demonstrating the potential of IIoT-based systems to support advanced connectivity and co-operation in an industrial setting.

In the CN-EPP, Cockpit4.0+ supports advanced connectivity and communication strategies. It lays the foundation for an industrial co-opetition ecosystem where rival SMEs can collaborate effectively, driving innovation and enhancing collective market responsiveness.

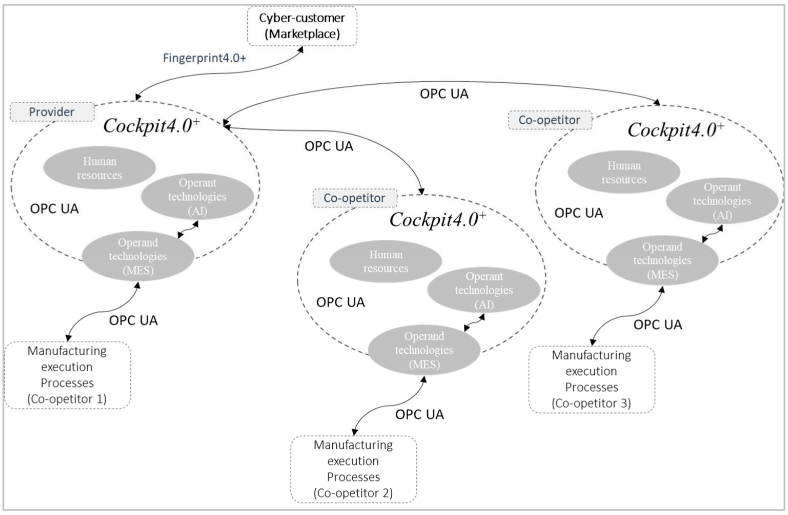

Figure 2. Co-opetition Network Experimental Pilot Project (CN-EPP).

6.2. Company Selection and Evaluation Metrics

The implementation of the CN-EPP involved planning and execution, particularly in the selection and engagement of participant companies from the OS-PT sector.

To begin with, direct and informal communication channels were established with the managing directors of potential participant companies. This approach facilitated a clear understanding of the project's scope and the potential future benefits for OS-PT SMEs.

A comprehensive confidentiality agreement was drafted to protect sensitive information about the companies' operations, clientele, employees, resources, and competitors, ensuring that all participants felt secure in sharing data. After thorough negotiations, three ornamental stone company managers representing the forefront of the sector agreed to participate in the experimental pilot project.

The project was overseen to maintain data integrity and confidentiality. This was achieved through direct, daily monitoring and recording of quantitative data using digital machinery and databases. Such stringent measures ensured that the data collected remained accurate and private, providing reliable insights into the effectiveness and impact of the IIoT implementation.

Drawing on insights from technology management and production literature (Jansen et al. 2004), it is crucial to understand the multifaceted nature of operational efficiency, which relies on production processes, logistics, and overarching business strategies (Serror et al. 2021; Pata and Silva 2022). To evaluate the impact of the co-opetition network for value cocreation in the OS-PT SMEs, two key performance indicators were defined: manufacturing value added and production–output ratio.

Manufacturing value added (KPI_MvA): This KPI represents the economic value added by the manufacturing process, assessing its contribution to overall business value. This measure helps gauge how effectively the manufacturing process adds economic value to the final product (Equation (1)).

$$\text{KPI\_MvA }(\%) = \left(\frac{\sum Sold\_parts_{(daily)}}{\sum Led\_parts_{(daily)}} \right) \cdot 100\% \tag{1}$$

Production–output ratio (KPI_PoR): This KPI quantifies the production volume relative to the resources used, providing insight into operational efficiency. It reflects the ability of the production process to maximize output while minimizing resource input (Equation (2)).

$$\text{KPI\_PoR }(\%) = \left(\frac{\sum Parts\_produced_{(daily)}}{\sum Manufacturing\_capacity)_{(daily)}} \right) \cdot 100\% \tag{2}$$

Once combined, these two KPIs can additionally provide insights into the stability and predictability of the improvements (Equation (3)).

$$\mathrm{KPI}(\sigma)\ (\%) = \sqrt[2]{\frac{\sum_1^n \left[KPI(MvA;PoR)_{(daily)} - \overline{KPI(MvA;PoR)_{(daily)}}\right]^2}{\left(Observations(R;PsO;MvA;PoR)_{(test\ period)}\right)}} \tag{3}$$

For examining the transition from current best practices (CB.Ps) to co-opetition network practices (CN.Ps) enhanced by the CN-EPP, a data collection strategy over two 54-day intervals was implemented, facilitating a comparative analysis of operational outcomes.

Phase 1—CB.Ps (17 April to 10 June 2023): This initial phase captured standard operations at three anonymized companies, designated "A", "B", and "C". It documented their reliance on internal resources for production and delivery, establishing essential baseline data for comparison.

Phase 2—CN.Ps (9 September to 14 November 2023): This phase evaluated the effects of integrating these companies into an IIoT-enhanced CN-EPP, marking a significant operational shift towards shared technologies and resources.

Throughout this study, data privacy and management were maintained under confidentiality agreements. All data were anonymized, referred to only by company labels, and managed according to stringent procedures. Data were recorded and exported to Excel files, ensuring their secure and consistent handling while enabling detailed analysis and preserving the privacy and proprietary information of the participants. This structured approach allowed for directly comparing operational outcomes and upheld data integrity throughout the research process. From these data, the KPIs from the three selected SMEs were assessed under CB.Ps and CN.Ps.

6.3. Insights into Value Addition in Manufacturing

Under CB.Ps, a KPI_MvA of 99.4% was recorded, indicating that most manufacturing operations successfully added value to the final product. Within CN.Ps, despite the scaling of operations, KPI-MvA improved to 99.9%. This enhancement suggests increased efficiency in the production process and reduced variance, as illustrated in Figure 3.

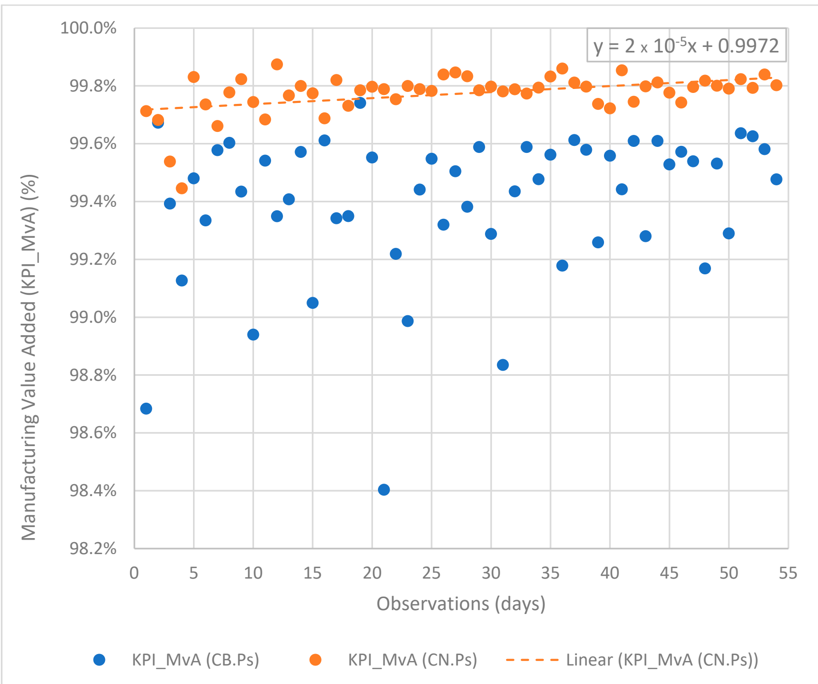

Figure 3. Daily trend in value added (CN.Ps).

This analysis shows that transitioning to CN.Ps not only maintained but slightly enhanced the value added by manufacturing processes despite increased operation volume.

6.4. Insights into Production–Output Ratio

Under CB.Ps, the findings revealed a KPI_PoR of 55.6%, with companies producing an average of 416 parts daily against a capacity of 590. Within CN.Ps, this ratio improved to 69.9%, indicating a substantial increase in production efficiency despite the constant production capacity.

The substantial increase of 14.3% in KPI_PoR under CN.Ps underscores the significant benefits of adopting these co-operative competition practices. This improvement signifies enhanced utilization of production capacities facilitated by the collaborative dynamics of co-opetition.

The gains in the production–output ratio under CN.Ps highlight significant advancements in production efficiency, optimizing resource utilization in manufacturing. The comparative analysis demonstrates the profound impact of adopting co-opetition strategies, which enhance the efficiency of production processes and outputs. In Figure 4, the linear regression trend line for KPI_MvA (CN.Ps) is presented, demonstrating the relationship between the daily observations and the production–output ratio.

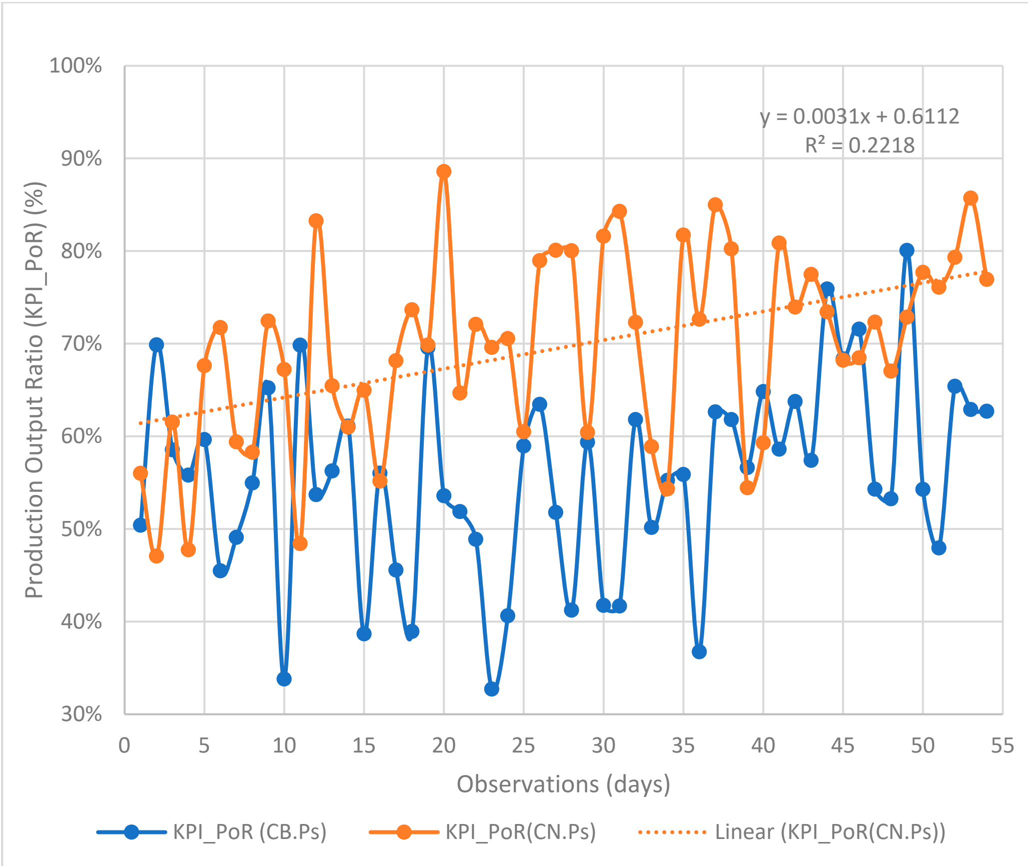

Figure 4. Daily trend in production–output ratio (CN.Ps).

The R-squared value for this regression is 0.2218. The correlation factor is 0.4709, indicating a moderate positive relationship between the variables. Despite this moderate daily growth, this result indicates that co-opetition networks positively contribute to this KPI. This results in an accumulated improvement of 14.1% in the production–output ratio under CN.Ps, highlighting significant benefits and enhanced utilization of production capacities due to collaborative co-opetition dynamics.

7. Discussion

Implementing the CN-EPP demonstrated notable improvements in KPIs for value addition in manufacturing and for the production–output ratio. Under the current best practices, KPI_MvA was recorded at 99.4%, which improved to 99.9% under the co-opetition network practices.

Similarly, KPI_PoR showed a substantial increase from 55.6% under CB.Ps to 69.9% under CN.Ps, highlighting significant production efficiency and resource utilization improvements. This 14.3% increase underscores the benefits of co-opetition, where shared technologies and resources lead to optimized production capacities and enhanced operational outcomes.

Moreover, insights into the stability and predictability of the improvements were assessed through KPI(σ), indicating an improvement of 71.9%, which proves enhanced manufacturing consistency. It indicates enhanced efficiency in the production process and reduced variance, affirming the efficacy of co-opetition strategies in maintaining and even enhancing operational performance despite increased volumes.

The successful application of Cockpit4.0+ within the CN-EPP illustrates the potential for IIoT-based systems to support advanced connectivity and communication strategies, creating an industrial ecosystem where rival SMEs can collaborate effectively. This integration aligns with the sector's inherent resilience and adaptability, supporting broader SDGs related to industry, innovation, and sustainable communities.

These findings confirm the hypothesis that a framework integrating the IIoT, S-D Logic, and service science can enhance value cocreation and effectively manage co-opetition among SMEs within the Portuguese ornamental stone sector.

8. Conclusions

Anchored in S-D Logic and service science principles, this study effectively demonstrates the significant advantages of employing a co-opetition strategy within SMEs by designing and implementing a co-opetition network for value cocreation embedding IIoT-based technologies in the Portuguese ornamental stone sector. Initially, this research study highlighted the pressing challenges SMEs face in adapting to rapid globalization and digitization, emphasizing the need for innovative frameworks that leverage competitive and collaborative dynamics to drive value creation and innovation.

The results from an experimental pilot project in the OS-PT showed that fostering an industrial ecosystem where SMEs engage in both competition and co-operation enabled by the IIoT can significantly improve operational efficiency. These improvements reflect enhanced operational efficiency and suggest reduced production variance and better resource utilization.

The successful application of co-opetition networks in the OS-PT sector has shown that integrating IIoT-based technologies can further enable effective co-opetition. This aligns with the sector's resilience and adaptability and supports broader socio-economic goals, including SDGs related to industry, innovation, and sustainable communities, thus promoting sustainable industrialization and resilience.

In conclusion, this research study provides a comprehensive framework that effectively addresses SMEs' operational challenges in the Portuguese ornamental stone (OS-PT) sector. It also sets a precedent for similar industries dealing with the complexities of digital and global procurement processes. By integrating the IIoT, S-D Logic, and service science, the proposed framework offers a robust solution for enhancing value cocreation and managing co-opetition, thereby contributing to sustainable industrial growth and resilience. The findings confirm the hypothesis that an integrated framework of the IIoT, S-D Logic, and service science significantly improves operational efficiency, reduces production variance, and optimizes resource utilization. The enhanced operational efficiency and optimized resource utilization contribute to SDG 9 (Industry, Innovation, and Infrastructure) by promoting sustainable industrialization and fostering innovation. Additionally, by supporting employment in inland regions, this framework contributes to SDG 8 (Decent Work and Economic Growth) and SDG 11 (Sustainable Cities and Communities).

While this study effectively demonstrates the significant advantages of employing a co-opetition strategy within SMEs in the Portuguese ornamental stone sector, several limitations must be acknowledged. These include the sector-specific focus, limited sample size, and variability in implementation, which may affect the generalizability of the findings to other industries and contexts.

Despite these limitations, the insights gained and the proposed framework integrating the IIoT, S-D Logic, and service science have the potential for broader applicability. Future research could explore the generalization of this framework across different sectors and geographic regions to validate its effectiveness in enhancing value cocreation and managing co-opetition among SMEs. By conducting comparative studies and pilot implementations in diverse industries, researchers can further refine and adapt the framework, ultimately contributing to a more universal model for industrial collaboration and innovation.

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