applied system innovation

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Coopetition with the Industrial IoT: A Service-Dominant Logic Approach

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Abstract: Abstract: This research addresses the critical gap in enabling effective coopetition networks through technological innovation with the development of Cockpit4.0+, an Industrial Internet of Things (IIoT) artefact tailored for small- and medium-sized enterprises (SMEs). By employing the principles of Service-Dominant Logic (S-D Logic) and leveraging the Design Science Research (DSR) methodology, Cockpit4.0+ represents a pioneering approach to incorporating the IIoT within ecosystems for value co-creation. This facilitates competition and cooperation among firms, enhancing the operational dynamics within SME networks. Evaluated by experts in the ornamental stone sector, a significant sector of the Portuguese economy, the system demonstrated a positive functional acceptance rate of 78.9%. An experimental test was conducted following the positive preliminary functional evaluation of Cockpit4.0+, especially among more digitally advanced companies. The findings revealed that the on-time delivery performance under current best practices (CB.Ps) was 67.1%. In contrast, implementing coopetition network practices (CN.Ps) increased on-time delivery to 77.5%. These positive evaluations of Cockpit4.0+ underscore the practical applicability of S-D Logic and provide fresh insights into the dynamics of coopetition, particularly beneficial for SMEs. Despite its promising results, the real-world efficacy of IIoT systems like Cockpit4.0+ requires further empirical studies to verify these findings. Future research should focus on examining the scalability of Cockpit4.0+ and its adaptability across various sectors and enhancing its cybersecurity measures to ensure its long-term success and broader adoption.

Keywords: coopetition; service ecosystems; networks; industrial IoT; S-D logic

Citation: da Silva, A.; Cardoso, A.J.M. Coopetition with the Industrial IoT: A Service-Dominant Logic Approach. *Appl. Syst. Innov.* **2024**, *7*, 47. https://doi.org/10.3390/asi7030047

Academic Editors: Mario Di Nardo and Maryam Gallab

Received: 21 March 2024
Revised: 17 May 2024
Accepted: 29 May 2024
Published: 31 May 2024

1. Introduction

In the dynamically shifting business environment, the integration of technological advancements with strategic partnerships among competitors, particularly within the European Union [1], has emerged as a critical strategy for securing competitive advantage, especially for small- and medium-sized enterprises (SMEs) [2,3]. This phenomenon, known as coopetition, marries the seemingly contradictory forces of cooperation and competition and has significantly captured the attention of management scholars [4].

The rise of the Industrial Internet of Things (IIoT) offers unparalleled opportunities for businesses to boost operational efficiency and foster innovation [5]. Ongoing developments in artificial intelligence (AI) and machine learning (ML) underscore the transformative potential of the IIoT [5]. When integrated with interoperability and accessibility, these technologies are crucial to boosting market responsiveness and facilitating value co-creation [6]. This is particularly evident through coopetition among manufacturing small- and medium-sized enterprises (SMEs) [7,8]. However, despite these advancements, there needs to be more solutions oriented towards leveraging the IIoT for coopetition networks, particularly among SMEs. A study by the BCG Henderson Institute, featured in the MIT Sloan Management Review, reveals a concerning 85% failure rate of coopetition networks in the short term, with success rates not exceeding 15% in the long term, predominantly in networks led by dominant firms like Microsoft and Amazon [9]. This highlights a significant research gap in understanding and facilitating successful coopetition networks for SMEs, which need to merge corporations' resources and market dominance.

Addressing this gap, this research aims to explore IIoT systems' multiple levels of interoperability and accessibility within SME networks and design an IIoT system for facilitating coopetition. Adopting the value co-creation perspective of Service-Dominant Logic (S-D Logic) [10], this study aims to develop an IoT artefact that empowers SME coopetition networks, fostering an ecosystem that encourages collaborative innovation and mutual value creation. By utilizing the Design Science Research (DSR) methodology, this research seeks to bridge the theoretical insights of S-D Logic with practical applications in the IIoT, specifically targeting SME coopetition [11].

This paper is structured to first explore the synergies and challenges of integrating coopetition networks with the IIoT through the lens of S-D Logic. After laying the theoretical groundwork, it discusses the methodology employed and details the design and development of the IIoT system, Cockpit4.0+, which is specifically tailored to facilitate coopetition among stone industry SMEs. The paper then presents a preliminary acceptance evaluation of the Cockpit4.0+ prototype, followed by an experimental pilot test. It concludes with a comprehensive discussion that synthesizes the findings, explores their broader implications, and proposes directions for future research.

1.1. Coopetition Networks for Value Co-Creation

S-D Logic represents a paradigm shift from the traditional goods-dominant logic, which emphasizes tangible products, to focus on service as the fundamental basis of economic exchange and value creation [12]. Introduced by Vargo and Lusch in 2004, this perspective has evolved into a comprehensive narrative that views economic activities through the lens of service-for-service exchanges within service ecosystems [13]. These ecosystems are orchestrated by institutions endogenously generated by the actors, underscoring value creation's collaborative nature [14]. Central to S-D Logic is the reconceptualization of exchange and value co-creation as primarily occurring through the provision of service, understood singularly rather than as multiple intangible outputs. In this context, service is defined as applying competencies (skills and knowledge) to benefit another entity or the entity itself, positioning resource integration as the cornerstone of value co-creation [15]. This perspective highlights that services can be exchanged directly, such as through personal interactions, or indirectly, via goods, which serve as vehicles for service delivery.

According to recent insights from Vargo et al. (2023a), adopting a systems viewpoint allows for conceptualizing markets and marketing phenomena as inherently relational, dynamic, and emergent. From these insights, technology is viewed as a crucial resource for networks, referred to as an increasing enabler of innovation [11], and technological advancements are viewed as enablers for firms' interactions [16], pushing networks to co-create more value for actors [12].

The various contributions in the literature underscore the role of S-D Logic in dissecting a wide range of empirical scenarios and enriching our theoretical comprehension of value co-creation processes [10]. Aligning with the S-D Logic premises, the discourse within the business literature increasingly recognizes coopetition networks as strategic, technology-supported networks [4]. This perspective positions technology not merely as a tool but as a central element that functions as an operant resource (initiator) and an operand resource (enabler). This dual role facilitates the formation of shared understandings among collective actors within ecosystems, enhancing collaboration and competitive advantage [17].

Under this view, technology's operant role in coopetition networks involves initiating new interactions and engagements, catalyzing value creation and exchange [15]. As an operand resource, technology is an enabler that supports these interactions, allowing for the seamless integration and utilization of resources across the network [18]. This nuanced role of technology underscores its critical importance in fostering an environment where businesses can collaborate and compete effectively.

This evolving understanding of technology's role in coopetition networks signals a significant shift towards more collaborative and adaptive networks. It highlights the necessity of rethinking traditional competition paradigms and advocates for a more integrated approach that embraces the complexities and opportunities of the digital age.

1.2. IIoT Challenges and Potential Solutions for Coopetition Enabling

Digitization involves transforming analogue information into digital format, facilitating data processing, storage, and transmission across digital platforms [19]. Building upon this foundation, digitalization expands the scope by integrating Information and Communication Technologies (ICTs) throughout the value chain. This integration challenges enterprises to evolve, adopting digital networks that revolutionize traditional concepts of workspace and resource distribution [20,21].

Within digitalization, the term "Internet of Things" (IoT) was introduced by Kevin Ashton, initially at Procter & Gamble and subsequently at MIT's Auto-ID Center in 1998 [22]. Ashton envisioned a world where "every object is part of the Internet", irrespective of the business proposition behind the IoT [23]. This vision has materialized over two decades, with advancements in wireless communication, sensors, and computing power. Today, the IoT encompasses uniquely identifiable objects capable of transmitting data over the Internet autonomously, minimizing or eliminating the need for human intervention [24,25]. The evolution of the IoT has facilitated the creation of interconnected networks, ushering in innovative service offerings such as remote monitoring and predictive maintenance [15]. These developments underscore the profound impact of digitization and digitalization on shaping the future of technology, enabling businesses to harness the power of the IoT for enhanced efficiency and novel solutions [26].

The IIoT, an extension of the IoT focusing on industrial applications, aims at elevating manufacturing SMEs to new efficiency levels through innovative, interconnected industrial systems [5,27]. These systems facilitate global connectivity and ensure meaningful communication between devices, paving the way for intelligent artefacts that respond to user interactions and contribute to complex value creation processes [28].

The IIoT represents a non-stop state-of-the-art updating, incorporating new improvements continuously and increasingly embedding the capability to take collaborative actions without humans [22], leading to a hyper-connected society and an increasingly global economy [29]. These collaborative capabilities [25] make IIoT technologies crucial to linking the shop floor directly with customers, enabling modern networks [30]. In technology-enabled networks, these collaborative actions happen not only among machines but also between providers and customers [5] and among rivals (coopetitors), from which value creation is created by multiple actors and determined by the beneficiary, thus converging to S-D Logic foundations [31].

1.3. Addressing the IIoT under an S-D Logic Perspective

Despite some recently developed IIoT-based systems representing methods in service knowledge [6–8], no solution oriented toward creating value through cooperation, namely, with manufacturing SMEs, was found.

Further bolstering the IoT and embedded systems era [32], the S-D Logic literature links the IoT and IIoT to ecosystems [15]. For S-D Logic, in ecosystems, resources are connected through any form of a sensor [23], enabling resources to be located, identified, and even operated upon [33] to promote more interactions among actors.

The S-D Logic focuses on value co-creation involving actors through operant and operand technologies [15], while the IIoT combines the global reach of the Internet with industrial capabilities to control, coordinate, and manage the physical world of goods, machines, factories, and infrastructure [21].

Aligned with this S-D Logic perspective on operand and operant resources [18], some authors in ICTs and service management refer to intelligent artefacts or systems able to execute specific functions [34] and reacting toward user interaction according to property sets of objects. However, for other authors, although this feasibility occurs successfully in some simple cases, in complex processes, the in-box thinking smart objects lead to creativity needing to be improved [35].

Viewing the IIoT through the S-D Logic perspective presents a strategic approach to leveraging technology for value co-creation. IIoT technologies facilitate the sharing of information and resources, enhancing the visibility and responsiveness of firms within networks [18]. By enabling more effective resource integration and service exchange, the IIoT empowers firms to engage in S-D Logic's core principle of creating value with and for their customers and partners. This integration highlights the role of technology not just as a tool or enabler but as a participatory resource in the service ecosystem, actively shaping opportunities for value creation [36].

From this perspective, IIoT technologies catalyze cooperation and competition among SMEs within coopetition networks. By providing a platform for data exchange and collaborative innovation, the IIoT enables firms to share insights and resources while maintaining competitive advantages [37,38]. This dual functionality supports the development of coopetition networks where SMEs can mitigate weaknesses like scale and explore new market opportunities without diluting their unique value propositions. The dynamic interplay facilitated by IIoT technologies underscores the complex nature of coopetition networks, where shared value creation and competitive differentiation coexist and reinforce each other.

1.4. IIoT Challenges and Potential Solutions for Coopetition Enabling

Drawing from the core principles of the IoT, the IIoT is heralded for elevating operational efficiency, particularly in small- and medium-sized manufacturing enterprises. It prioritizes advancing smart, autonomous, and interconnected industrial processes to boost the manufacturing industry's competitive advantage [39]. This approach underscores the transition towards intelligent manufacturing and highlights the IIoT's role in fostering a more connected, efficient, and competitive industrial landscape.

However, anchoring coopetition networks in the IIoT faces numerous challenges. Success in these networks largely hinges on the presence of key players, with leading companies playing a central role in the survival and profitability of digital networks [40]. This trend towards high failure rates supports the literature's focus on the crucial impact of "keystone" members on the viability of ecosystems. Notably, there have been no successful cases of coopetition networks composed solely of SMEs [9].

These challenges include issues related to data security and ensuring the confidentiality and integrity of shared information in a landscape where entities might also be competitors [41]. Interoperability, or the ability of diverse systems and organizations to work together, becomes critical in environments where collaboration is essential for scale but must be balanced against competitive interests [42]. Furthermore, intellectual property management assumes heightened importance as entities navigate the fine line between sharing enough to co-create value while safeguarding their competitive advantages [43].

In the context of coopetition, the stakes of technological integration are heightened. Entities must navigate the dual objectives of leveraging shared platforms for mutual benefit while maintaining enough competitive edge to survive and thrive. This balancing act requires a strategic approach to technology adoption and collaboration, where the goal is to win or lose deals not just as individual entities but as interconnected parts of a larger ecosystem. In the state of the art, the success of one can contaminate the entire network forward, illustrating the complex but potentially rewarding nature of coopetition facilitated by IIoT artefacts.

From these challenges grounded in the S-D Logic foundations, to enhance value co-creation in coopetition networks, the IIoT artefact must ensure the actors' expectations by fulfilling, requiring capabilities: (1) operant and operand technological capabilities—the seamless adaptation to coopetition networks' dynamic environments [44]; (2) technical, semantic, and pragmatic interoperability—which ensures that the artefact can not only communicate and operate across diverse technological platforms (technical interoperability) but also interpret and utilize the information meaningfully (semantic interoperability) and support actionable insights and decisions (pragmatic interoperability) [12]; (3) accessibility and usability for network actors—this focus acknowledges the importance of human-centered design principles, ensuring that the system can be effectively utilized by a broad spectrum of users to facilitate collaboration and value co-creation [45]; and (4) facilitation of simultaneous collaboration among competitors—recognizing the inherent complexities of coopetition, the artefact must enable and enhance collaboration among competing entities from the lead to winning or losing the business opportunity [4].

2. Methodology

DSR is a distinctive methodological paradigm transcending traditional research frameworks such as positivist, interpretive, and critical approaches. It focuses on creating and systematically evaluating artefacts to address real-world issues [46]. This methodology, as detailed by Peffers et al. (2007) and Baskerville et al. (2018), is centered on the conception and assessment of a wide array of artefacts, including but not limited to models, methods, constructs, software, and technological systems [47]. The primary goal of DSR is to devise practical solutions that effectively tackle existing problems and enrich our theoretical understanding of the problems at hand and the proposed solutions [48]. This approach is particularly relevant in the IIoT context, where the design and implementation of innovative artefacts can significantly contribute to advancing both practical capabilities and scholarly knowledge.

Accordingly, as prescribed by the DSR methodology, this study developed an IoT artefact to facilitate coopetition networks among SMEs. Subsequently, it was evaluated by experts representing manufacturing SMEs.

The Cockpit4.0 system, as introduced by Silva et al. (2020), was developed within the framework of the Inovstone4.0 R&D Project. This project, financed by the European Union under the Mineral Resources Cluster Action Plan, aimed to harness advanced technologies and software for the natural stone industry. Specifically, Cockpit4.0 was designed to facilitate connectivity between ornamental stone companies and the cyber market [49]. Beyond serving as a mediator resource that interacts with cyber customers, Cockpit4.0 is equipped with the innovative "fingerprint4.0" feature, including a dual-compartment cargo vehicle: the first compartment houses detailed descriptions of the co-created product, which may include comments, notes, remarks, or other pertinent information. The second compartment carries the IFC/XML code, facilitating the creation of smart objects. Cockpit4.0 is considered state-of-the-art within the stone industry [50], showcasing the transformative potential of the IIoT to revolutionize traditional market dynamics by enhancing direct interaction and collaboration. However, it cannot connect competing rivals within a coopetition network.

Analyzing the Cockpit4.0 system through the S-D Logic framework reveals its effectiveness as a dynamic facilitator of cyber value offerings, enhancing service provision [51]. This perspective highlights an opportunity to push the boundaries of state-of-the-art in-stone processing by leveraging advanced technological capabilities. Significantly, it promotes coopetition by connecting the shop floors of manufacturing rivals within a network to co-create increased value for all stakeholders. By harnessing the integration of resources from these rivals, there is a substantial potential to enhance value creation across networks, ultimately providing superior service to customers.

To address the challenge of coopetition network failures, particularly in the absence of key companies, an evolved version of the system, Cockpit4.0+, is proposed. This advancement aims to bridge the gap, ensuring higher industry ecosystem connectivity, efficiency, and responsiveness. Committing to this evolution aims to foster an environment where SMEs can flourish, benefiting from collaborative innovation and strategic flexibility. Cockpit4.0+ represents a step forward in realizing a more integrated and cooperative industry landscape, where the synergy between technology and coopetition principles can lead to sustainable growth and enhanced customer satisfaction.

2.1. Cockpit4.0+ Development

The Cockpit4.0+ system, grounded in S-D Logic, requires effective orchestration of the interplay between operant (initiator) and operand (actuator) resources, a central strategy for enhancing coopetition networks [52]. This strategic integration necessitates a deliberate approach to technology implementation, where operant capabilities initiate actions and operand resources—physical or tangible assets—execute or respond to these initiatives. By synergizing these capabilities, Cockpit4.0+ drives innovation, boosts efficiency, and fosters collaboration among SMEs. This harmonious integration potentially elevates SME competitiveness and nurtures a dynamic environment where coopetition flourishes, merging cooperation with competition to discover new value and opportunities in the market. Additionally, Cockpit4.0+ must ensure that each coopetitor only shares the desired information, assuring that other network members maintain this reciprocity.

By incorporating these concepts into the existing Cockpit4.0 framework, the new Cockpit4.0+ emerges as an advanced version designed to facilitate network coopetition. This enhancement requires (1) a modular architecture that seamlessly integrates with SMEs' current digital infrastructures, including ERP and CRM systems, as well as manufacturing equipment; (2) a commitment to data protection through the use of advanced encryption methods and secure exchange protocols, which safeguard sensitive information against digital threats and ensure data integrity; (3) user-friendly interfaces that are accessible to a broad range of users, promoting engagement across various platforms, including mobile devices. Furthermore, Cockpit4.0+ encompasses a comprehensive upgrade of the existing Cockpit4.0 modules, including replacing sensors with more advanced technology, enhanced cloud computing capabilities, and high-speed networking equipment. Through the strategic amalgamation of these operant and operand resources, the Cockpit4.0+ system is set to significantly boost innovation, efficiency, and collaboration within the competitive sphere of SMEs, thereby advancing coopetition networks.

2.2. Operant Capabilities: Artificial Intelligence and Machine Learning

By incorporating artificial intelligence (AI) and machine learning (ML), the Cockpit4.0+ system discreetly enhances the network resources of coopetitors, such as machines and inventory. This integration facilitates sophisticated data analysis, market trend forecasting, and the generation of actionable intelligence. Such capabilities support dynamic pricing strategies, predictive maintenance, and the customization of offerings to meet specific customer needs. The AI module within Cockpit4.0+ provides real-time advisories to each coopetitor about the optimal combination of resources—including those from competitors—throughout the sales cycle, from lead acquisition to the outcome of a deal. Meanwhile, the ML module continuously offers real-time insights into the performance optimization of various resources, including manufacturing assets, human resources, and financial capital.

2.3. Multiple Levels of Interoperability

The interoperability of Cockpit4.0+ must extend its capabilities beyond the foundational layers, weaving a complex fabric of robust and flexible connectivity. By embedding the OPC Unified Architecture (OPC UA), Cockpit4.0+ ensures seamless data exchange across various platforms and devices and paves the way for advanced collaborative frameworks within the industrial sector (Figure 1).

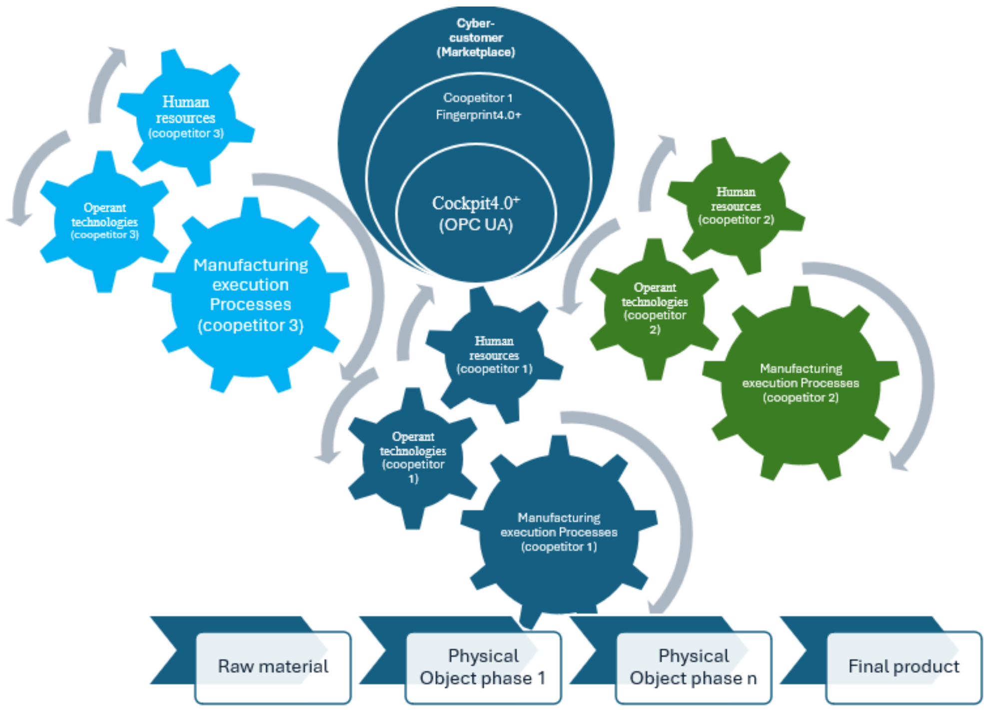

Figure 1. OPC UA interoperability mechanisms in coopetition technology-enabled networks.

Through the advanced interoperability facilitated by Cockpit4.0+, the networks foster deeper collaboration among actors, allowing them to leverage shared resources and capabilities more effectively. This enhanced level of connectivity ensures that all network participants, regardless of their technological infrastructure, can partake in the value creation process.

Leveraging resource density and digital materiality must be embedded at the heart of Cockpit4.0+ to become instrumental in redefining how value is co-created within networks. This way, Cockpit4.0+ facilitates the liquefication and unbundling of network resources, thereby enabling the dynamic recombination of capabilities tailored to meet specific customer needs. This approach enhances flexibility and amplifies the potential for innovation in the network. In particular, the digital materiality mechanism [21] underscores the system's capacity to bridge the gap between the virtual and physical realms. By enabling the manipulation of digital representations of physical objects, Cockpit4.0+ allows for a more nuanced and sophisticated approach to product development and customization. This capability is critical for SMEs seeking to differentiate themselves through unique value propositions [21].

Embedding the OPC UA into the Cockpit4.0+ architecture underscores a commitment to establishing a genuinely interoperable ecosystem. This decision aligns with the system's overarching goal of facilitating seamless and secure communication across all levels of operation—from machine-to-machine interactions to broader device-to-cloud data exchanges. The OPC UA's role in ensuring data integrity and security is paramount, particularly when handling sensitive information or executing complex transactions across the network. Furthermore, the integration of the OPC UA supports the pre-validation process, allowing stakeholders to assess and refine value propositions before they enter the manufacturing phase. This capability is essential to maintaining high standards of quality and compliance, as well as for minimizing waste and optimizing resource use.

2.4. Network Actors' Accessibility and Usability

The Cockpit4.0+ system must strongly emphasize making the digital ecosystem accessible and user-friendly for all participants, grounding its design in human-centered principles that align with S-D Logic. This perspective views value creation as a collaborative process among network actors, emphasizing resource integration and exchange. By designing Cockpit4.0+ to facilitate cooperation—even among competitors—Cockpit4.0+ sets the stage for secure and efficient service exchanges that elevate the network's collective value proposition. As key mechanisms for enhancing usability and accessibility, Cockpit4.0+ embodies systemic assemblages and architectural modules for transactions and service (Figure 2).

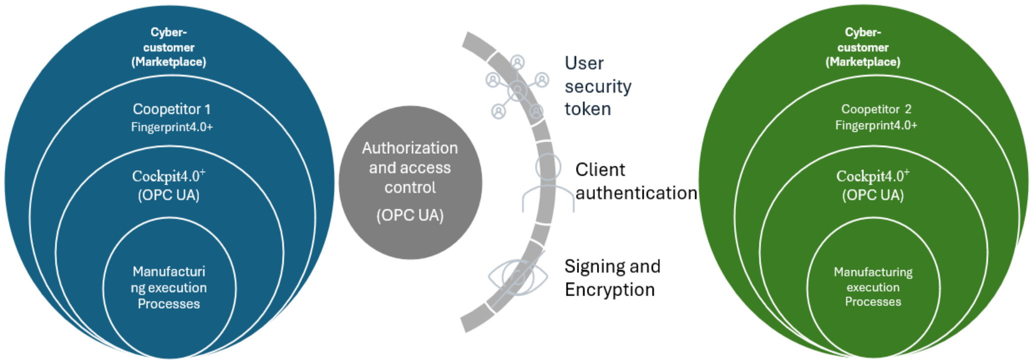

Figure 2. OPC UA security mechanisms in coopetition technology-enabled networks.

Cockpit4.0+ must adopt a holistic approach by integrating various technological components into cohesive assemblages. These assemblages are more than the sum of their parts. They offer enhanced functionalities by leveraging the interconnectedness of diverse technological systems, reflecting the S-D Logic view that service ecosystems are intricate structures, combining various social and technological aggregation levels. The system's architecture is thus designed to facilitate this integration, ensuring that all network actors can interact seamlessly within this diverse technological landscape.

Cockpit4.0+ must feature modular designs to allow for the flexible reconfiguration of products and services to meet different needs, facilitating personalization and customization. This modular approach can support the disintermediation and fragmentation of physical products, a concept that the S-D Logic literature suggests can foster value within ecosystems. By enabling the tailored recombination of operant and operand functionalities, Cockpit4.0+ acts as a dynamic architectural framework that adapts to and supports the evolving requirements of the network's participants.

The OPC UA's comprehensive security features—including digitally signed certificates and encryption—are crucial to preventing data tampering and eavesdropping, thus maintaining the integrity and confidentiality of network exchanges. The adoption of the OPC UA facilitates the creation of a coopetition network wherein multiple instances of the Cockpit4.0+ system can represent various stakeholders, fostering value co-creation across the dimensions of customers, rivals, and providers. This setup promotes sustained collaboration throughout the lifecycle of business opportunities, from their inception to their conclusion, regardless of the outcome.

By embedding systemic assemblages and modular architectural designs into the foundation of Cockpit4.0+ and leveraging the robust security and interoperability of the OPC UA, the system is poised to offer a secure, intuitive platform. This IIoT system can support dynamic collaboration and value co-creation, enabling technology-enabled networks to thrive aiming to redefine coopetition networks, making them more inclusive, adaptable, and conducive to innovation and mutual success for SMEs.

2.5. Algorithm: Cockpit4.0+ System Development

The development of the Cockpit4.0+ system initiates by identifying specific features and functionalities critical to addressing the dynamics of coopetition. These elements provide a foundation for an understanding of, engagement with, and the collective pursuit of new business opportunities. The Cockpit4.0+ development process involved designing an algorithm that integrates operant and operand technological capabilities. This integration ensures interoperability across different levels, enhances accessibility and usability for network participants, and promotes effective collaboration among competitors. The algorithm, detailed in Table 1, encompasses the core functionalities, and ensures a systematic implementation of the system's features as described below.

Table 1. Systematic implementation algorithm for Cockpit4.0+ features.

Algorithm Steps	Core Functionalities
Initialize System Core Components	Set up the foundational architecture, including cloud computing, high-speed networking, and basic security protocols.
Integrate Operant Technological Capabilities	Implement AI/ML for data analysis and trend prediction. Develop modular architecture for ERP/CRM integration. Enforce data protection with encryption. Design intuitive, mobile-compatible UI. Design intuitive user interface that ensures accessibility and mobile compatibility.
Incorporate Operand Capabilities	Install devices for real-time monitoring. Utilize cloud computing for scalable storage/processing. Ensure secure high-speed data transmission. Connect with digital marketplaces.
Interoperability Across Levels	Establish technical, semantic, and pragmatic interoperability pathways.
Implement S-D Logic Foundations	Integrate resource density mechanisms and digital materiality mechanisms.
Deploy OPC UA	Use OPC UA for interoperability and security measures like digitally signed certificates and encryption.
Enhance Usability and Accessibility	Apply human-centered design. Develop modules for transaction/service customization. Create interconnected technological components.
Facilitate Coopetition Collaboration	Implement advanced communication, data-sharing tools, APIs for third-party integration, and privacy mechanisms. Provide platforms for co-creation and innovation. Establish governance and trust-building features.
Testing and Deployment	Conduct comprehensive testing (usability, security, and interoperability). Deploy for pilot testing with SMEs. Collect feedback and adjust.
Launch and Monitor	Launch Cockpit4.0+ for broader use. Monitor performance and user feedback. Implement updates and enhancements.

Advanced communication and data-sharing tools: (i) secure messaging and file sharing—the implementation of encrypted communication channels and secure file-sharing capabilities ensures the safe exchange of information and resources among competitors, maintaining confidentiality and integrity; (ii) real-time collaboration spaces—the provision of tools like shared digital whiteboards and co-editing documents facilitates seamless collaboration, enabling participants to work together effectively from various locations.

Access control and privacy mechanisms: (i) granular permission settings—a sophisticated access control system allows for precise control over shared data and resources, safeguarding sensitive information by restricting access based on roles or needs; (ii) data anonymization and aggregation—employing data anonymization techniques to share insights without compromising competitive advantages, enabling the collective benefit from aggregated data without revealing proprietary information.

Interoperability and integration capabilities: (i) APIs for third-party integration—robust APIs ensure smooth integration with existing systems and platforms, streamlining workflows and facilitating efficient data exchange among competitors; (ii) standards compliance—ensuring the system adheres to industry standards for data exchange and interoperability, facilitating seamless communication and collaboration across diverse technological environments.

Co-creation and innovation platforms: (i) idea management tools—tools that support the collection, development, and evaluation of ideas collaboratively, driving innovation within the coopetition framework; (ii) prototype testing environments—virtual spaces where new products or services can be tested and refined together, speeding up the innovation process and reducing the time to market.

Conflict resolution and governance structures: (i) transparent governance mechanisms—clear rules and governance structures are established for managing coopetition, ensuring all parties have input in decision-making processes and access to dispute resolution mechanisms; (ii) performance tracking and reporting—integrating tools for monitoring collaboration progress and outcomes, ensuring transparency and accountability for all network participants.

Trust building and relationship management: (i) reputation systems: a system that allows companies to rate their experiences with competitors, fostering trust and reliability within the network; (ii) facilitated networking events—organizing events and workshops to strengthen relationships among competitors, promoting a culture of openness and mutual respect.

By integrating these features into Cockpit4.0+, the system has been fully developed to support and actively promote collaboration among competitors. The algorithm lays out a structured pathway for developing the Cockpit4.0+ system, ensuring that all critical aspects—from operant and operand technological capabilities to interoperability, usability, and coopetition facilitation—are systematically addressed.

A preliminary evaluation was undertaken within the Portuguese ornamental stone (OS-PT) sector. This assessment aimed to gauge the functional acceptance of Cockpit4.0+ and explore its potential to enhance coopetition among stone SMEs.

2.6. Functional Acceptance and Evaluation of Cockpit4.0+ Prototype

The OS-PT sector, a cornerstone of Portugal's rich cultural heritage and forward-looking innovation, has significantly contributed to iconic stone monuments worldwide since the 15th century [53]. Recent data from the Portuguese Stone Federation (2022) illuminate the sector's substantial economic impact: exporting to 116 countries, ranking as the ninth most significant player in the World International Stone Trade, and securing the second position globally regarding international trade per capita [54]. With exports outstripping imports by 660% and a significant share of exports reaching markets outside Europe, the industry boasts a turnover of EUR 1.230 million. It supports over 16,600 direct jobs, making it a critical employment source, particularly in inland regions [55].

A preliminary evaluation involved technical experts and engineers from 24 OS-PT SMEs. These SMEs were strategically selected to represent a wide range of digital maturity levels within the OS-PT sector, thus providing a diverse and representative sample for the evaluation. This approach yielded valuable insights into accepting the Cockpit4.0+ prototype's functionalities across various stages of digital readiness among the SMEs involved.

For the study, each participating company was assigned a digital level (DL) based on comprehensive site visits, 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; and DL#4: all machines are connected to the ERP system and can connect to Building Information Modeling (BIM) architects' stations.

The evaluation included a detailed assessment of each company's digital production equipment, management, integration processes with production, and involvement in digital marketplaces. The survey was structured into four actions.

First Action (Introduction): 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, with a tangible demonstration of the Cockpit interface. Second Action (Explanation): Explanation of the Cockpit's functionalities regarding innovation, usefulness, cybersecurity, and usability in facilitating coopetition among rival SMEs, including features for resource sharing without prior partner knowledge, maintaining commercial confidentiality, and automated resource allocation based on buyer decisions. Third Action (Questions): Participants were asked to rate, on a scale from one to five, their opinion on Cockpit4.0+ regarding technological disruptiveness, usefulness, cybersecurity, and usability. Fourth Action (Data Collection): The survey was conducted throughout 2023, with the data anonymized to maintain confidentiality and documented in an Excel file. Average responses are detailed in Table 2.

Table 2. Summary of average responses from the questionnaire.

Cockpit4.0+ Functional Acceptance (Average)	Disruptive Innovation	Company's Usefulness	Cybersecurity	Usability	Average Rating
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 functional acceptance	4.8	3.2	3.3	4.5	3.9

The aggregated ratings from respondents underscored the perceived innovation of the Cockpit4.0+ system, with an impressive average score of 3.9 out of 5. This highlights the prototype's potential functional efficacy within the sector. Notably, the perceived usefulness of the system exhibited a positive correlation with the companies' digital maturity. Among the most digitally advanced respondents (DL#4), the system achieved high scores, averaging 4.8 out of 5.

Even though cybersecurity emerged as an area for improvement, with an average rating of 3.3 out of 5, the prototype demonstrated significant promise as a tool for enabling coopetition, especially among SMEs with higher digital levels.

Converting the quantitative data from the questionnaire into percentages reveals an overall positive acceptance rate of 78.9% for the Cockpit4.0+ prototype, demonstrating its considerable potential to foster coopetition within SME networks (Figure 3). The feedback particularly underscores the exceptional value of the system for entities at the forefront of digital integration. However, a focused review and the enhancement of the system's security features are advisable, given the cybersecurity concerns. Strengthening these aspects will bolster confidence in the prototype and enhance its overall utility and acceptance among SMEs.

The positive preliminary functional evaluation of Cockpit4.0+, especially by the DL#4 respondents, created solid conditions for the next step: conducting the first experimental test. However, the lower acceptance rates among respondents with lower digital levels (DL#0, DL#1, and DL#2) suggest that these companies are not yet prepared to integrate collaborative software like Cockpit4.0+. This integration requires a digital mindset and needs to be improved in these less digitally mature enterprises.

Using the Cockpit4.0+ prototype, a strategic implementation of an experimental pilot test began for the first objective evaluation of Cockpit4.0+. Two companies from the DL#4 group, which rated Cockpit4.0+ the highest in functional acceptance, were formally invited to participate in this pilot test (Figure 4). These two companies, recognized as leaders in the Portuguese stone sector, have all their machines connected to the ERP system, which connects to BIM architects' stations. This setup represents the OS-PT sector's current best practices (CB.Ps). A comprehensive confidentiality agreement was drafted to protect sensitive information regarding the companies' operations, clientele, employees, resources, and competitors.

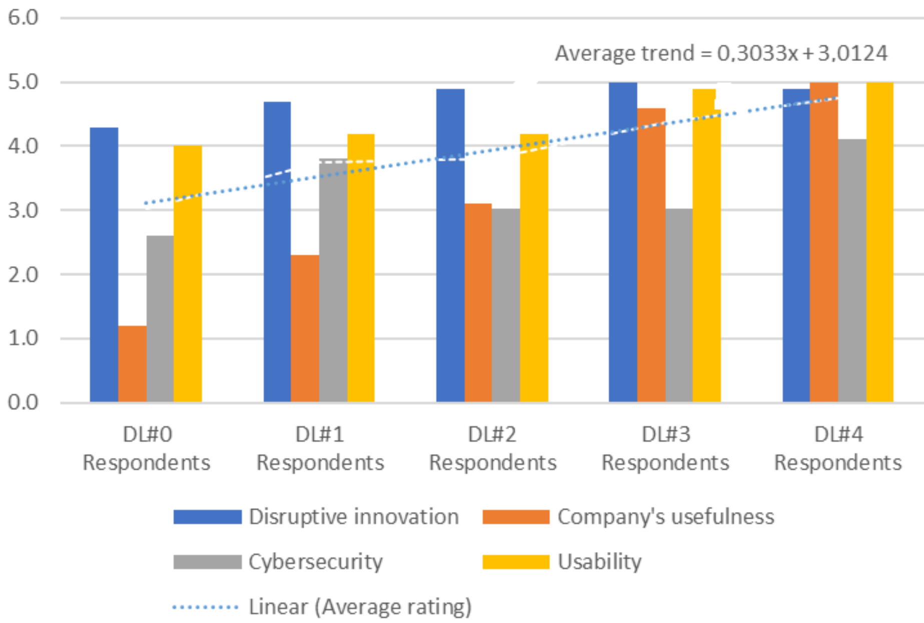

Figure 3. Evaluation of Cockpit4.0+ by SMEs in the stone manufacturing sector.

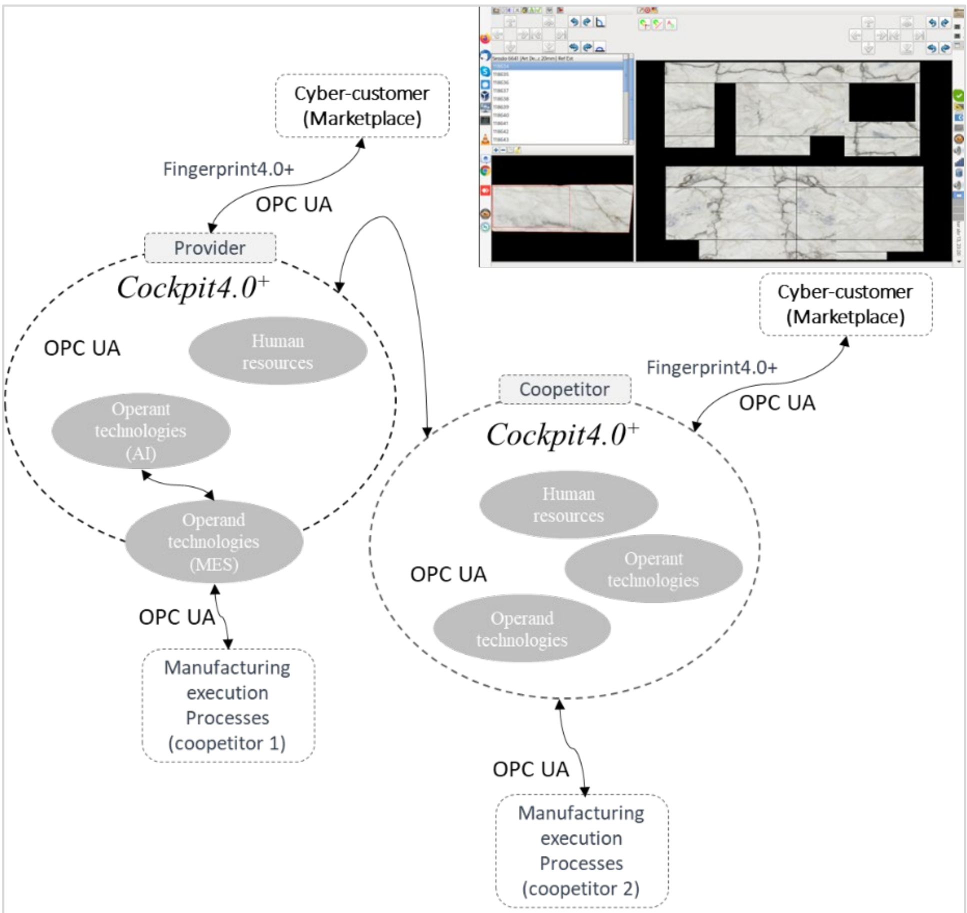

Figure 4. Implementation of the Cockpit4.0+ experimental pilot test.

As BIM integrates the crucial aspect of time, marking a significant evolution in project management and coordination within the construction industry [56], stone fabricators must enhance their scheduling, coordination, and productivity processes to respond to BIM-shaped industry demands effectively. Therefore, "On-Time Delivery KPI" was selected as the key performance indicator (KPI_{OtD}) for evaluating stone fabricators' responses, reflecting their ability to meet project deadlines (Equation (1)) consistently.

$$KPI_{OtD}\,(\%) = \sum_{1}^{n} \left(\frac{parts\_delivered\_on\_time_{(daily)}}{\sum parts\_delivered)_{(daily)}} \right) \quad (1)$$

Improvements in KPI_{OtD} directly enhance the effectiveness of ensuring timely project execution and schedule adherence.

This study employed a data collection strategy across two fifty-four-day intervals to explore the transition from CB.Ps to cooperative network practices (CN.Ps) enhanced by Cockpit4.0+, enabling a robust comparative analysis of on-time delivery outcomes.

CB.P phase: The first interval focused on capturing standard operations at the two anonymized companies. This baseline phase documented each company's reliance on internal resources for production and delivery, providing essential reference data for subsequent comparisons.

CN.P phase: The second interval assessed the effects of integrating these entities into a coopetition-based network enhanced by the Cockpit4.0+ prototype.

Data management and privacy were rigorously maintained throughout the study in compliance with confidentiality agreements. All data were anonymized and referred to only by company labels. Data collection, recording, and exportation procedures were followed, with results exported to Excel files. This ensured a secure and consistent approach to data handling, enabling detailed analysis while safeguarding the privacy and proprietary information of the participating companies. The data collected were used to assess KPI_{OtD} under CB.Ps and CN.Ps, as summarized in Table 3.

Table 3. Summary of average data collected daily.

Data Type	Description	CB.Ps—Average Data (Daily)	CN.Ps—Average Data (Daily)
Data type 1	Parts delivered daily	339	454
Data type 2	Parts delivered on time	240	358
KPI	On-time delivery	0.671	0.775

Based on these findings, under CB.Ps, the on-time delivery performance was recorded as 67.1%, with 240 out of 339 parts being delivered as scheduled. In contrast, CN.Ps resulted in a significant increase in KPI_{OtD} to 77.5%, with 358 out of 454 parts being delivered on time. Figure 5 shows the daily average on-time delivery performance for both CB.Ps and CN.Ps.

These results demonstrate that by transitioning to a coopetition network facilitated by Cockpit4.0+, the OS-PT companies experienced substantial improvements in on-time delivery performance.

In summary, this evaluation text of the Cockpit4.0+ prototype confirmed the preliminary functionalities. By focusing on the identified areas for improvement and capitalizing on its existing strengths, the system is strategically positioned to significantly influence the OS-PT sector digital transformation. Specifically, it promises to enhance dynamic and secure competition networks, which is essential for evolving competitive landscapes.

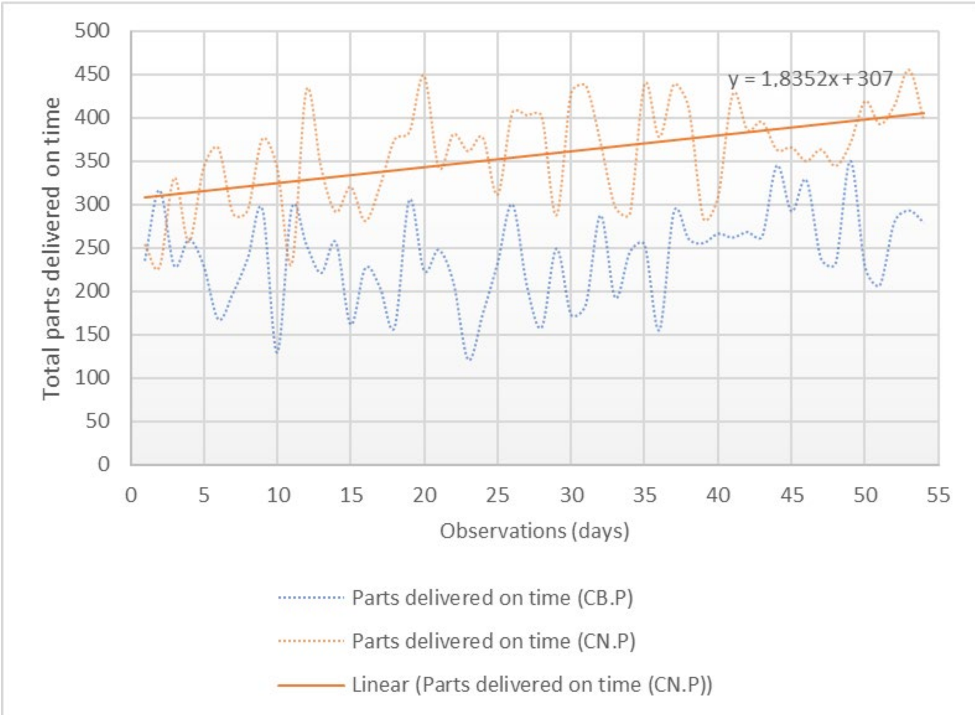

Figure 5. Daily trend in on-time-delivery.

3. Conclusions

This study has highlighted the significant potential of the Cockpit4.0+ prototype to enhance operational efficiency and collaborative practices within the Portuguese stone manufacturing sector (OS-PT). The sector, deeply embedded in Portugal's cultural heritage and innovation landscape, plays a vital role in the global stone trade. The findings underscore the prototype's promise in fostering digital transformation, mainly through improved coopetition strategies among SMEs.

The OS-PT sector's historical and economic significance is substantial, with exports reaching 116 countries and a turnover of EUR 1.230 million. This sector supports over 16,600 direct jobs, making it crucial for regional employment. Given its pivotal role, adopting advanced digital tools like Cockpit4.0+ is essential to maintaining and enhancing its competitive edge.

The preliminary functional evaluation of Cockpit4.0+ involved technical experts and engineers from 24 OS-PT SMEs, categorized across five digital maturity levels (DL#0 to DL#4), emphasizing the prototype's strategic fit for digitally advanced environments.

The experimental pilot test, involving two DL#4 companies, further validated the system's efficacy. These results demonstrate that the Cockpit4.0+ system can significantly contribute to the digital transformation of the OS-PT sector. By focusing on the identified areas for improvement and leveraging its strengths, the system is well positioned to foster dynamic and secure coopetition networks. It is particularly relevant in a landscape where advanced management practices, potentially aligned with ISO standards, can further refine and enhance operational efficiency.

Future research should explore integrating advanced management systems based on ISO standards to complement the Cockpit4.0+ prototype. Such integration could provide a robust framework for continuous improvement and standardization across the sector, offering valuable insights for other industries aiming to adopt similar digital transformation initiatives.

The Cockpit4.0+ prototype holds significant promise for revolutionizing the OS-PT sector. Its strategic implementation can drive the sector's digital evolution, enhance collaborative practices, and sustain its competitive edge in the global market.

Despite the promising results, this study has several limitations. First, the evaluation was conducted in a specific sector, limiting the generalizability of the findings. Future research should replicate the study in diverse sectors and geographic regions to assess scalability and adaptability comprehensively. Further refinement of the system's algorithms and a closer examination of cybersecurity dimensions are imperative for ensuring robustness and security in practical applications.

Author Contributions: A.d.S.—conceptualization, original draft writing, and review and editing; A.J.M.C.—conceptualization, original draft writing, and review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data supporting this study's findings are available from the corresponding author, Agostinho da Silva, upon request.

Conflicts of Interest: The authors declare no conflicts of interest.

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