Journal of
Theoretical and Applied Electronic Commerce Research

Article

Enhancing Building Information Modeling Effectiveness Through Coopetition and the Industrial Internet of Things

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Abstract: The construction industry plays a crucial role in the global economy but faces significant challenges, including inefficiencies, high costs, and environmental impacts. Although Building Information Modeling (BIM) has been widely adopted as a solution to these issues, its practical impact remains limited. This study investigates how manufacturers can enhance their contributions to improve BIM's effectiveness, proposing that coopetition practices—combining competition and cooperation—can positively influence these contributions, thereby enhancing the benefits of BIM. To explore this hypothesis, an Experimental Coopetition Network was implemented in the Portuguese ornamental stone (POS) sector, utilizing Industrial IoT technology to facilitate collaboration among selected companies. The study assessed the impact of coopetition practices on key performance indicators related to BIM, including on-time delivery, labor productivity, and CO_2 emissions. The findings demonstrate significant improvements in scheduling, operational efficiency, and environmental sustainability, validating the hypothesis that coopetition practices can enhance manufacturers' contributions to BIM. These results suggest that coopetition practices contribute to better project outcomes, increased competitiveness, and sustainability within the construction industry. Despite the promising results, the study acknowledges limitations such as the scope of the sample size and observation periods, indicating areas for future research. This research contributes to the theoretical framework of coopetition, aligning with the United Nations Sustainable Development Goals (SDGs), and provides valuable insights for industry practitioners and policymakers seeking to implement more sustainable construction practices.

Keywords: coopetition; construction industry; BIM; sustainable development goals

Citation: da Silva, A.; Marques Cardoso, A.J. Enhancing Building Information Modeling Effectiveness Through Coopetition and the Industrial Internet of Things. *J. Theor. Appl. Electron. Commer. Res.* **2024**, *19*, 3137–3153. https://doi.org/10.3390/jtaer19040152

Academic Editor: Zorica Bogdanović

Received: 1 October 2024
Revised: 8 November 2024
Accepted: 12 November 2024
Published: 15 November 2024

1. Introduction

The construction industry is a cornerstone of the global economy, with growth projected to exceed USD 4.2 trillion over the next 15 years [1]. However, the United Nations Environment Programme (2023) identifies the sector as a significant contributor to global greenhouse gas emissions, accounting for 37% of the total amount. The substantial carbon footprint associated with producing and using materials such as cement, steel, and aluminum underscores the urgent need for innovative cooperation models in building and construction [2].

Despite its critical role, the industry continues to grapple with persistent challenges, including inefficiencies, high costs, extended project timelines, and considerable environmental impacts [3]. In response, governments and researchers have advocated for the adoption of Building Information Modeling (BIM) [4], a technology designed to enhance efficiency and sustainability in construction through comprehensive digital representations of physical and functional characteristics [5].

This situation explains the significant attention given over the past decade by governments and academics to the widespread adoption of BIM on a global scale [6]. BIM is seen as the technology capable of transforming the current construction paradigm, which is not only unsustainable but also needs more transparency, generates substantial waste, and consequently remains inaccessible to many families [4].

However, despite the increased focus on BIM and its numerous advantages, its practical impact has remained limited [7]. Moreover, while BIM has been extensively promoted and adopted, a critical gap persists in understanding how manufacturers can fully capitalize on its benefits [8]. Each project component influences BIM's various dimensions differently, meaning the effectiveness of BIM depends on how well each component aligns with these dimensional requirements [9]. To unlock BIM's full potential, fabricators must effectively address these dimensions [10].

Given these challenges, a critical question arises: How can manufacturers enhance their contributions to improve BIM's effectiveness in the construction industry? A promising strategy to address this challenge lies in coopetition [11], which blends elements of competition and cooperation to achieve mutual benefits [12]. The hypothesis suggests that coopetition practices can positively influence manufacturers' contributions, enhancing BIM's benefits.

To test this hypothesis, this study explores the potential of coopetition practices to meet BIM requirements through a case study in the Portuguese ornamental stone (POS) sector. This investigation involves an Experimental Coopetition Network facilitated by Industrial Internet of Things (Industrial IoT) technology, encompassing selected companies within the POS sector. The study aims to assess the tangible benefits of coopetition practices across various indicators related to BIM dimensions that can enhance BIM's effectiveness. The findings are expected to offer valuable insights into the role of manufacturers in BIM-enhanced construction projects and the potential of coopetition to reduce costs, time, and carbon emissions.

To address these industry-wide challenges, BIM has been identified as a crucial tool in reshaping construction practices. BIM not only offers a pathway to enhanced efficiency and sustainability but also provides a framework for overcoming the sector's most persistent obstacles. By fostering transparency and streamlining processes, BIM holds the potential to redefine project management and collaboration across the industry. The following section explores BIM's role as a transformative catalyst in the construction industry, outlining its dimensions and applications that support a more efficient, cost-effective, and sustainable approach to construction.

2. BIM as a Catalyst for an Efficient Construction Industry

Traditional management practices in the construction industry have long been criticized for generating unnecessary waste [9], leading to high costs, extended project timelines, and considerable ecological impacts [13]. In response, governments and industry professionals have advocated for the gradual adoption of BIM to enhance transparency and efficiency [6].

BIM has emerged as a natural successor to Computer-Aided Design (CAD) in the construction sector [14]. Propelled by government mandates, the construction industry increasingly integrates BIM into its operations, driven by objectives to reduce costs, shorten project durations, and align with sustainability goals [15]. This integration marks a substantial shift towards more responsible and efficient design and construction practices [16].

BIM represents a fundamental shift in conceptualizing, executing, and managing construction projects in this context. At its core, BIM provides a digital twin of the physical construction [17], capturing every detail in a digital model that accurately reflects the physical reality [18]. However, this has led to some confusion within the industry regarding the distinction between BIM maturity levels and dimensions [16]. BIM maturity refers to the sophistication of information exchange within the supply chain, highlighting the collaborative capabilities of the involved parties [19]. In contrast, BIM dimensions refer to the various data types linked to a model, offering more profound insights into the project's lifecycle [20].

Incorporating data dimensions within a BIM allows for an unparalleled understanding of the construction process [21]. Designers and stakeholders can gain a comprehensive view of the project, which encompasses the initial design, work stages, and delivery methods for each component and both the budgeting and maintenance plans. These dimensions promote a more refined approach to project management [22].

While the first three dimensions (BIM.3D) pertain to the solid geometry of objects, the fourth dimension (BIM.4D) introduces the crucial element of time, marking a significant advancement in project management and coordination within the construction industry [4]. By integrating project timelines directly into digital models, BIM.4D offers a dynamic and interactive method for planning, enabling the real-time visualization of construction sequences [14].

The fifth dimension (BIM.5D) addresses cost management within construction projects by linking financial data with each component in the digital model [5]. This comprehensive approach transforms budgeting into a dynamic, detail-oriented process [23], allowing for immediate visibility and continuous updates on the financial implications of design decisions and manufacturing changes throughout the project [24].

The sixth dimension (BIM.6D) is centered on sustainability, incorporating environmental metrics directly into the building information model [25]. This dimension provides real-time insights into the ecological footprint of materials and processes throughout a project's lifecycle, empowering professionals to make decisions that support sustainability objectives [15].

Beyond these dimensions, BIM also encompasses maintenance and construction safety, offering a holistic perspective from project inception to demolition [10]. However, fabricators must effectively engage with and contribute to BIM dimensions to fully realize BIM's potential.

In parallel with the transformative role of BIM in enhancing construction efficiency and sustainability, the strategic concept of "coopetition" has gained prominence as a potential enabler of BIM's full benefits. By blending cooperation and competition, coopetition offers a unique approach to help industry stakeholders overcome competitive barriers while driving collective value creation. The following section provides a comprehensive review of the coopetition literature, exploring its evolution, definitions, and theoretical underpinnings, which form the basis for understanding how coopetition practices might be leveraged to enhance BIM's impact in the construction sector.

3. Literature Review

The concept of "coopetition" gained significant traction in business strategy through the seminal work of Nalebuff and Brandenburger (1997), marking a crucial shift in the understanding of competitive dynamics [26]. Over time, coopetition has attracted considerable attention in strategic management, evolving through various interpretations and applications [27].

Despite its widespread discussion, the definition of coopetition remains diverse, with interpretations varying across different goals, relationships, and organizational contexts [28]. It has been described as a strategy that simultaneously pursues cooperation and competition among firms [29], a hybrid activity within the same business entities [30], and a complex interplay that influences competitive dynamics among different market participants [12].

At the intersection of coopetition and networks, a strategic orientation focused on innovation emerges, which is crucial for firms aiming to close competitive gaps and effectively manage market challenges [31]. This orientation underscores the role of coopetition in navigating competitive landscapes and highlights its potential as a catalyst for transformative growth and resilience [32]. Various studies present a broad spectrum of findings, emphasizing the need for a more unified and thorough exploration of value co-creation processes within these complex networks [33].

A comprehensive review by Meena, Dhir, and Sushil (2023) reveals that coopetition has been analyzed through various theoretical lenses, including Game Theory, the Resource-Based View, Paradox Theory, Transaction Cost Theory, and Network Theory [31]. While each perspective offers valuable insights, they often address the concept within specific boundaries. Despite the diversity in definitions, the essence of coopetition converges on a hybrid relationship where competition and collaboration intertwine to benefit the participating companies [34]. This concept is particularly relevant in digital supply chains [32].

The hypothesis that coopetition practices can positively influence construction manufacturers' contributions in enhancing BIM benefits arose from viewing coopetition practices as strategic paradigms that leverage dual simultaneous forces to drive innovation, enhance competitive advantage, and achieve collective success. To test this hypothesis, the study explores the potential of coopetition practices to meet BIM's requirements through a case study in the POS industry involving an Experimental Coopetition Network facilitated by an Industrial IoT system encompassing selected enterprises within the POS sector.

Based on the literature review and theoretical foundations, this study aims to address the following research question:

- Research Question: How can coopetition practices enhance manufacturers' contributions to improve the effectiveness of Building Information Modeling (BIM) in the construction industry?

  To answer this question, the following hypotheses are proposed:

Hypothesis 1 (H1): *Coopetition practices positively influence manufacturers' on-time delivery performance, thereby improving the BIM 4D (time management) dimension in construction projects.*

Hypothesis 2 (H2): *Coopetition practices enhance labor productivity among manufacturers, contributing to cost savings and optimizing the BIM 5D (cost management) dimension.*

Hypothesis 3 (H3): *Coopetition practices reduce CO_2 emissions associated with manufacturing processes, supporting the BIM 6D (sustainability) dimension and promoting environmental sustainability in construction.*

These hypotheses will be tested using a case study in the Portuguese ornamental stone sector, employing an Experimental Coopetition Network facilitated by Industrial IoT technology to gather data on the impact of coopetition on key BIM dimensions.

The following section details the structured methodology used to implement an Experimental Coopetition Network, outlining the participant selection, technology integration, and data collection processes that provide insights into how coopetition practices might enhance manufacturers' contributions to BIM effectiveness.

4. Methodology

The case study approach was selected to explore the impact of coopetition practices on BIM effectiveness in the Portuguese ornamental stone sector. This method provides a structured framework for analyzing events, collecting data, and reporting results, allowing for an in-depth understanding of the phenomenon within its context (Hsu, 2016; [35,36].

To test the hypothesis that coopetition practices can enhance manufacturers' contributions to BIM, an Experimental Coopetition Network was implemented. The methodology involves the following structured steps, as illustrated in Table 1.

Table 1. Research procedure for implementing the Experimental Coopetition Network.

Step	Description
Step 1: Identification and Selection of Companies	Identify and select stone companies that meet participation criteria, including technological capability, willingness to collaborate, and relevance to the construction industry.
Step 2: Technology Integration	Establish the necessary technology to connect selected companies within the Experimental Coopetition Network. Set up and ensure real-time data collection and analysis capabilities.
Step 3: Definition of Metrics and KPIs	Define metrics and KPIs for evaluating coopetition practices, focusing on BIM dimensions: time efficiency (BIM 4D), cost-effectiveness (BIM 5D), and carbon reduction (BIM 6D).
Step 4: Data Collection and Analysis	Collect data on the defined KPIs through the Experimental Coopetition Network, monitoring the network's performance in real-time. Analyze the data to evaluate improvements.
Step 5: Hypothesis Testing	Assess whether the data support the hypothesis that coopetition practices enhance BIM benefits.

1. Identification and Selection of Companies: Stone companies were identified based on specific criteria essential for participation, including their technological readiness, openness to coopetition, and strategic relevance to the construction industry. This step was crucial in ensuring that selected companies could meaningfully contribute to and benefit from the Experimental Coopetition Network.
2. Technology Integration: The selected companies were integrated into the Experimental Coopetition Network, with technology set up to facilitate real-time data sharing and analysis. The network utilized Industrial IoT systems to connect participants, ensuring seamless communication and data flow necessary for BIM collaboration.
3. Definition of Metrics and KPIs: To evaluate the impact of coopetition practices on BIM, key performance indicators (KPIs) were defined across three BIM dimensions:
   - ○ BIM 4D (Time Efficiency): Assessed through on-time delivery rates.
   - ○ BIM 5D (Cost-Effectiveness): Measured through labor productivity indicators.
   - ○ BIM 6D (Sustainability): Evaluated by calculating carbon emissions per unit produced.
4. Data Collection and Analysis: Data were collected on the defined KPIs, with real-time monitoring being used to capture the performance of each company under coopetition practices. The collected data were analyzed to gauge improvements in BIM dimensions and to generate insights into how coopetition practices influence project outcomes.
5. Hypothesis Testing: Based on the insights derived from the collected data, hypothesis testing was conducted to assess whether coopetition practices positively impact BIM benefits. This step involved a statistical analysis to determine the validity of the hypotheses proposed.

This structured methodology provides a systematic approach to assessing the role of coopetition practices in enhancing BIM effectiveness within the Portuguese ornamental stone sector. By clearly outlining the research procedure, this framework allows for replicability and offers a foundation for future studies to expand on these findings in other sectors.

4.1. Selecting Participants

The Portuguese ornamental stone sector, deeply rooted in the nation's cultural heritage, has been a cornerstone of architectural and construction achievements worldwide since the 15th century [37]. Renowned for its high-quality stone and engineering expertise, the sector embodies generations of accumulated knowledge and craftsmanship, making it an integral part of Portugal's identity [38]. As the global market continues to evolve, Portugal has firmly established itself as a leading producer of stone products [39], seamlessly integrating into the international construction industry. This success highlights the sector's competitive edge despite the country's modest geographic size [11].

With a diverse array of companies, the Portuguese ornamental stone sector offers a broad spectrum of operational environments. This diversity makes it an ideal population for testing the hypothesis that coopetition practices can positively influence manufacturers' contributions to improve BIM's effectiveness in the construction industry. The sector's established global presence—exporting to 116 countries and holding a significant position in the world stone trade—underscores its relevance to the study. According to the Portuguese Stone Federation (2022), the ornamental stone sector not only ranks as the ninth-most significant player in the World International Stone Trade, but it also secures the second position globally in terms of international trade per capita [40]. The industry's substantial turnover of EUR 1.230 million and its support of over 16,600 direct jobs further emphasize its economic importance [41].

The sector's mix of tradition and modernity and its readiness to engage in digital transformation make it an exemplary case for testing the hypothesis. The selection of participants for the Experimental Coopetition Network is based on criteria such as technological capability, openness to collaboration, and strategic importance within the industry. This approach ensures that the study captures a representative sample of the sector, providing valuable insights into the broader applicability of coopetition practices in enhancing BIM benefits.

Recognizing these characteristics in the Portuguese ornamental stone sector, the first step involved establishing direct and informal communication channels with the managing directors of potential participant companies, a process that uncovered three significant operational challenges:

Technological Capability: The first challenge was the limited number of companies with production systems capable of real-time connectivity to meet BIM procurement requirements. Given that BIM demands high levels of precision and interoperability, only a subset of 43 companies out of the 661 in the sector were found to have the necessary digital infrastructure. After in-person evaluations of these 43 companies, 23 were pre-selected based on their ability to integrate with an Industrial IoT platform.

Logistical Complexity and Costs: The second challenge involved the logistical complexities and costs of implementing the Experimental Coopetition Network and operationalizing data collection. The experimental nature of the project, combined with budget constraints, required careful planning to ensure its viability. Given the budget limitations, the number of participating companies had to be reduced to a minimum to manage costs effectively and create a controlled environment for testing the feasibility of BIM integration. The data collection period was also limited to two months to ensure the project remained within budget while providing meaningful insights.

Data Sharing Reluctance: The third and perhaps most critical challenge was the reluctance of companies to share sensitive data, a common issue in industries where proprietary knowledge is a critical competitive asset. In the context of BIM, where the success of a project relies on transparent and accurate data exchange, this reluctance posed a significant barrier. To overcome this, a comprehensive confidentiality agreement was developed to reassure participating companies that their competitive positions would not be compromised by their involvement in the network. This agreement covered all aspects of operations, including clientele, employee information, resources, and competitive strategies.

As a result of these strategic considerations, three ornamental stone companies formally committed to participating in the study, with confidentiality agreements signed to protect their interests. To maintain the integrity of the research and safeguard the identities of the companies involved, they are referred to anonymously as "POS.1", "POS.2", and "POS.3".

This Experimental Coopetition Network functioned as a laboratory for collecting data on independent variables to explore the benefits of coopetition practices, treated as dependent variables, in testing the hypothesis that coopetition practices can positively influence manufacturers' contributions and enhance the benefits of BIM. By fostering a coopetition environment, these selected companies could improve their ability to meet BIM requirements more effectively.

With complete participant selection and confidentiality agreements in place, the study established the Experimental Coopetition Network. This network aimed to leverage advanced Industrial IoT technology, creating a collaborative environment where participating companies could integrate their operations seamlessly. The following section describes the implementation process of this network, focusing on the technological infrastructure, including Cockpit4.0+, and the steps taken to enable secure, real-time data exchange between firms to support BIM applications.

4.2. Implementation of the Experimental Coopetition Network

The advent of the IoT marks a transformative era, significantly impacting industries through advanced sensor technologies that enhance connectivity and data exchange [42]. Building on traditional IoT frameworks, the Industrial IoT introduces intelligence into industrial environments, enabling direct device-to-device communication and creating intelligent systems that dynamically adapt to user interactions, enhancing value co-creation [43]. Empirical studies highlight the transformative potential of Industrial IoT-based innovations, particularly in offering new services such as remote control and predictive maintenance [44]. These capabilities improve operational efficiency and open new avenues for value co-creation within coopetition frameworks, expanding service portfolios and enhancing enterprises' competitive and cooperative capacities [45].

In the Portuguese ornamental stone sector, for instance, an illustrative example of the Industrial IoT is the development of Cockpit4.0 [46], designed to connect stone companies with the digital marketplace [47]. This artifact refines product specifications and fosters collaborative interactions among machines, providers, and customers, ultimately enhancing customization and operational efficiency [48]. The current state of Cockpit4.0 exemplifies Industrial IoT's capacity to reshape market dynamics through direct engagement and cooperative efforts.

Although Industrial IoT development was not the primary focus of this research, Cockpit4.0, representing the state-of-the-art in the Ornamental Stone sector [48], was identified as a foundational platform for transforming operational technology within the Experimental Coopetition Network. To fully leverage its potential, Cockpit4.0 was enhanced with new functionalities, such as secure connections between competing firms, leading to an advanced version called Cockpit4.0+ for this research. This upgraded Industrial IoT system, specifically designed to connect ornamental stone companies, brought enhanced technological capabilities and fostered a collaborative industrial environment conducive to a real Experimental Coopetition Network.

A key component of Cockpit4.0+ is the integration of Open Platform Communications Unified Architecture (OPC-UA), a cross-platform, open-source standard (IEC62541) for data exchange from sensors to cloud applications, developed by the OPC Foundation [49]. OPC-UA enables secure and efficient data exchange, facilitating seamless connectivity between factory floor equipment and control systems, even across different communication protocols.

By embedding OPC-UA protocols, Cockpit4.0+ addresses gaps in connectivity, efficiency, and responsiveness, creating a network where companies can thrive through collective innovation and adaptive strategies. Integrating technological innovations, such as artificial intelligence, further promotes a collaborative industrial environment, ensuring sustainable operations and competitiveness among participating companies.

Once Cockpit4.0+ was finalized, even in its prototype form, the implementation of the Experimental Coopetition Network began. Three POSs companies were formally connected (Figure 1) into a real coopetition network. These companies could now operate in certain domains as if they were a single factory linked to BIM architects' stations, regardless of their geographical locations.

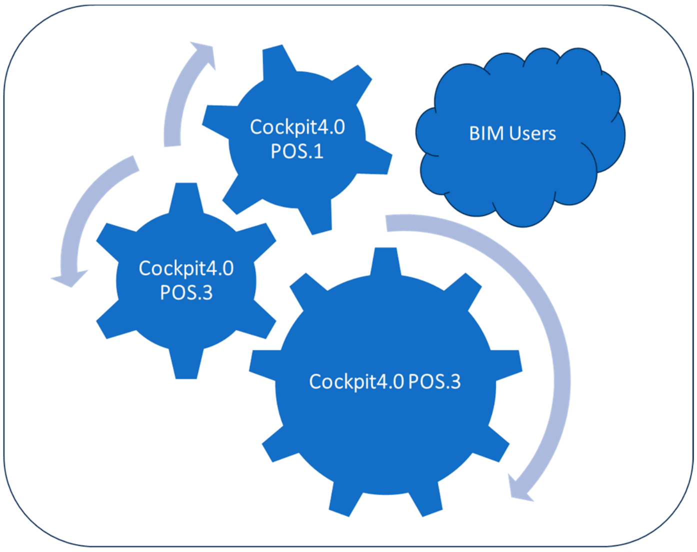

Figure 1. Experimental Coopetition Network for the Portuguese ornamental stone sector.

In each POS company involved in the case study, a Cockpit4.0+ system was installed, ensuring secure connectivity among companies and facilitating potential connections to BIM stations interested in prescribing customized stone globally.

With the Experimental Coopetition Network successfully established, the study defined specific metrics and KPIs necessary for assessing the impact of coopetition practices on BIM integration. The following section outlines the KPIs selected for this purpose, each aligned with the core dimensions of BIM (4D, 5D, and 6D). These metrics provide a structured approach to measuring improvements in time management, cost efficiency, and environmental sustainability—key areas where coopetition practices are expected to enhance BIM's effectiveness in the construction industry.

4.3. Defining Metrics and KPIs for BIM Integration

BIM's effectiveness in construction projects heavily depends on how well each component aligns with the requirements of the various BIM dimensions. The BIM.4D dimension integrates the element of time into the digital model, significantly enhancing time synchronization, accountability, and communication throughout the project lifecycle. BIM.4D enables the real-time visualization of construction sequences, which is essential for dynamic and timely project delivery.

To meet the stringent requirements of BIM.4D, manufacturers must optimize their scheduling, coordination, and productivity processes, emphasizing timely delivery [14]. The alignment of manufacturing timelines with project schedules is critical in ensuring that the overall project adheres to its planned timeline, thereby maintaining the integrity of the BIM model.

The on-time delivery (KPI_{OtD}) indicator is crucial for assessing a manufacturer's ability to consistently meet project deadlines [7]. This indicator measures the percentage of stone parts delivered within the agreed timeframe (PDoT) over the total parts produced (PD), reflecting the manufacturer's efficiency in adhering to the scheduled timeline (Equation (1)). KPI_{OtD} is not just a measure of logistical performance; it directly influences the effectiveness of BIM.4D by ensuring that all components arrive on time and in sequence, as required by the project schedule.

$$KPI_{OtD}(\%) = \sum_1^n \left(\frac{PDoT_{(daily)}}{PD_{(daily)}} \right) \tag{1}$$

Improvements in KPI_{OtD} are therefore critical for enhancing the overall effectiveness of BIM.4D. A higher KPI_{OtD} means that the manufacturer is more reliably delivering components as per the project's timeline, which supports the accurate and timely execution of the construction plan. This alignment between delivery schedules and project timelines minimizes delays and disruptions, ensuring that the benefits of BIM.4D BIM—such as improved planning, better resource management, and enhanced project coordination—are fully realized.

The BIM.5D dimension integrates cost data with the 3D model, enabling comprehensive budget and financial management throughout the project lifecycle [24]. BIM.5D is critical for optimizing project costs by providing stakeholders with detailed financial insights directly linked to the construction model [22]. This integration allows for more accurate cost estimation, resource allocation, and ongoing cost monitoring, essential for keeping projects within budget while maintaining high-quality standards.

To fully leverage the benefits of BIM.5D, manufacturers must ensure that the components they produce meet required quality standards and do so at the lowest possible cost. Achieving this requires improvements in manufacturing efficiency, which can be accomplished by optimizing human and technological resources [16].

Drawing from lean management principles, industry efficiency is often measured through productivity indicators that relate output to labor input. For this case study, labor productivity (KPI_{LP}) has been selected as a critical metric to evaluate efficiency. KPI_{LP} measures the number of parts or tasks completed (PD) by a worker (LI) within a specified timeframe, providing a clear indication of labor efficiency (Equation (2)).

$$KPI_{LP}(\%) = \sum_{1}^{n} \left(\frac{PD_{(daily)}}{LI_{(daily)}} \right) \quad (2)$$

Enhancing KPI_{LP} is directly aligned with the requirements of BIM.5D. A higher KPI_{LP} indicates that a manufacturer is producing more with the same or fewer resources, effectively reducing costs without compromising quality. This increased efficiency supports the goals of BIM.5D by lowering overall construction costs while maintaining the project's financial health.

By improving labor productivity, stone companies can contribute to more efficient cost management throughout the project lifecycle. This alignment between labor productivity and cost efficiency is crucial for maximizing the benefits of BIM.5D, ensuring that projects are completed within budget and provide better value for stakeholders. The focus on optimizing labor inputs while maintaining output quality directly impacts the project's financial performance, making KPI_{LP} a vital metric for evaluating the success of BIM.5D in BIM-enabled construction projects.

The BIM.6D emphasizes sustainability by integrating environmental data into the BIM model, with the primary goal of reducing the ecological footprint of construction projects [15]. BIM.6D requires manufacturers to optimize the use of raw materials and processes to minimize the environmental impact of the building materials they produce [50]. This focus on sustainability is crucial in global efforts to combat climate change and promote environmentally responsible construction practices.

To evaluate how healthy fabricators are meeting the sustainability goals of BIM.6D, the CO_2 equivalent (CO_2-eq) factor is used as a critical metric [51]. This factor converts the energy consumed during production into equivalent carbon dioxide emissions, providing a standardized measure of the environmental impact associated with the manufacturing process.

Given the interconnected nature of power networks within the European Union, calculating the CO_2 equivalent for individual countries can be complex. For example, in Portugal, energy demands during critical periods often necessitate importing electricity from other European countries. These imports can significantly influence the carbon intensity of the energy used in production. Therefore, the average European CO_2 equivalent factor is applied for this case study to ensure a more accurate and standardized environmental impact assessment [52].

According to the European Electricity Review (2023), the carbon intensity of electricity across Europe varies significantly due to the diverse energy mixes of EU member states [53]. For instance, countries like Sweden and France have much lower carbon intensities (below 50 g CO_2/kWh) because of their heavy reliance on nuclear and renewable energy sources. In contrast, countries like Poland and Estonia have much higher carbon intensities (over 600 g CO_2/kWh) due to their dependence on coal and other fossil fuels. As of 2022, the EU's average carbon intensity of electricity generation was 276 g of CO_2 per kilowatt-hour (g CO_2/kWh) [53].

Equation (3) can be employed to calculate the CO_2 equivalent ($KPI_{CO_2\text{-}eq}$) for producing parts, reflecting the energy consumed (EC) per part delivered (PD). This metric allows for a precise evaluation of the environmental impact of manufacturing processes, enabling fabricators to assess their alignment with the sustainability objectives of BIM.6D.

By reducing the $KPI_{CO_2\text{-}eq}$, manufacturers can directly contribute to the environmental goals of BIM.6D, ensuring that their operations are efficient and environmentally responsible. This alignment with BIM.6D requirements is essential for promoting sustainable practices within the construction industry and achieving broader environmental targets, such as those outlined in the Sustainable Development Goals (SDGs).

$KPI_{CO_2\text{-}eq}$

$$KPI_{CO_2-eq}(\mathrm{KgCO_2/part}) = \sum\nolimits_1^n \left(0.276 \times \frac{EC_{(daily)}}{PD_{(daily)}}\right) \tag{3}$$

Reductions in $KPI_{CO_2\text{-}eq}$ directly contribute to lowering the construction industry's CO_2 emissions and support SDG 11—Sustainable Cities and Communities—by promoting environmentally responsible practices and reducing urban carbon footprints.

With the KPIs established, the study progressed to an empirical assessment of the impact of coopetition practices on these metrics. The following section details the comparative analysis conducted over two distinct 54-day intervals, capturing baseline practices versus coopetition practices. This approach allows for an in-depth evaluation of how coopetition influences time efficiency, cost-effectiveness, and environmental impact, thereby providing valuable insights into the effectiveness of BIM dimensions within the Experimental Coopetition Network.

5. Data Collection and Analysis

A comprehensive data collection strategy was implemented over two fifty-four-day intervals to evaluate the impact of coopetition practices on the selected KPIs. This approach allowed for a comparison between the current or baseline practices (B.P), and a new set of practices termed coopetition practices (C.P). Under C.P, companies collaborated by sharing manufacturing resources and raw material stocks to better capitalize on market opportunities presented by BIM users.

The first 54-day period, conducted in the first half of 2023, focused on documenting the standard operations of the anonymized companies. This baseline phase provided essential reference data by capturing each company's reliance on internal resources for production and delivery.

The data collected during this period established a benchmark for subsequent comparisons (Table 2).

Table 2. Data collected during baseline practices (B.P).

Data ID	Independent Variables	Units	POS.1	POS.2	POS.3	Average (B.P)
Data 1	PD	Parts/day	362	185	469	339
Data 2	PDoT	Parts/day	258	116	364	240
Data 3	LI	hours/day	56	27	65	49
Data 4	EC	kWh/day	5023	2477	6577	4692

The second 54-day period, concluding in the second half of 2023, assessed the impact of integrating the same three companies into the Experimental Coopetition Network. During this period, the newly installed Cockpit4.0+ systems enabled real-time information sharing about manufacturing resources and raw material stocks among the companies (Table 3).

Table 3. Data collected during coopetition practices (C.P).

Data ID	Independent Variables	Units	POS.1	POS.2	POS.3	Average (B.P)
Data 5	PD	Parts/day	477	309	577	454
Data 6	PDoT	Parts/day	377	234	462	358
Data 7	LI	hours/day	56	27	65	49
Data 8	EC	kWh/day	4036	2472	5705	4071

Data management and privacy protocols were maintained throughout the study by confidentiality agreements. All data were anonymized, and companies were referred to only by their labels. Data collection, recording, and exportation followed established procedures, with results exported to Excel files as detailed in the methodology section. This approach ensured secure and consistent data handling, enabling detailed analysis while safeguarding the privacy and proprietary information of the participating companies. The assessment of KPIs as stone companies transitioned from B.P to C.P is presented in Table 4.

Table 4. Assessment of KPIs for B.P and C.P.

KPI	Dependent Variables	Units	B.P	C.P	Gain
KPI_{OtD}	On-time delivery	parts/parts	0.671	0.775	15.6%
KPI_{LP}	Labor productivity	parts/working_hours	6.84	8.72	27.38%
$KPI_{CO_2\text{-eq}}$	CO_2 emissions	$KgCO_2$/part	3.41	2.68	21.8%

Based on the data collected, the following section will interpret the results to assess whether coopetition practices can positively impact the ability of stone manufacturers to enhance the benefits of BIM [10]. This interpretation will provide insights into whether the hypothesis is validated or refuted, guiding conclusions about the efficacy of coopetition practices in this context.

Following the analysis of baseline and coopetition practices across key performance indicators, the study now focuses on testing the hypothesis. This section assesses how coopetition practices enhance BIM benefits by examining the data on time efficiency, labor productivity, and environmental impact. Each BIM dimension—4D, 5D, and 6D—will be evaluated, providing insights into whether the hypothesis is validated or refuted based on the improvements observed in the Experimental Coopetition Network.

6. Hypothesis Testing

6.1. Responding to BIM.4D: Enhancing On-Time Delivery Gains Through Coopetition Networks

The BIM.4D integrates the critical element of time, significantly advancing project management and coordination within the construction industry. Effective time management ensures that construction projects adhere to planned schedules, minimizing delays and enhancing overall project efficiency.

To evaluate how coopetition practices influence the ability of stone manufacturers to meet the requirements of BIM.4D, the KPI_{OtD} was assessed to determine the gains companies experienced when transitioning from baseline practices to coopetition practices. According to the data collected, under B.P, the average KPI_{OtD} was 67.1%, with 240 out of 339 parts delivered as scheduled. In contrast, under C.P, the KPI_{OtD} significantly increased to 77.5%, with 358 out of 454 parts delivered on time. This improvement underscores the effectiveness of C.P in ensuring more reliable customer deliveries and meeting project timelines.

The trend in on-time delivery during the observation periods provides further insights into the consistency and reliability of delivery services. Figure 2 illustrates the percentage of deliveries made on time each day, showing how coopetition practices led to a gradual improvement in delivery performance.

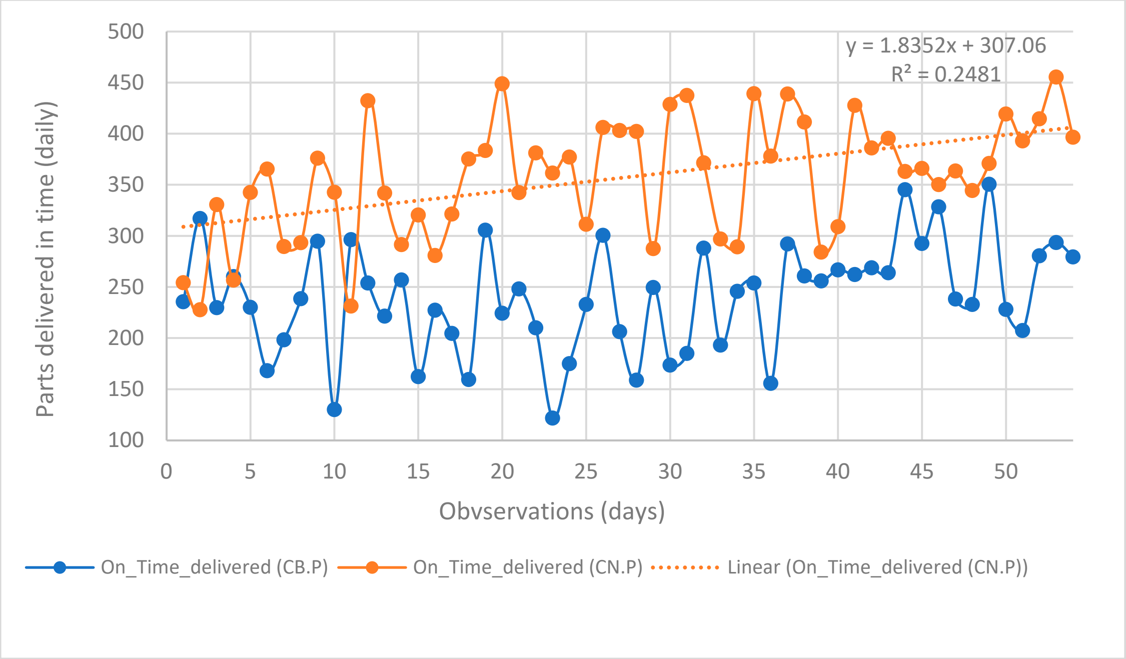

Figure 2. On-time delivery trend across 54 daily observations.

The positive slope of 1.8352 indicates a steady increase in the number of parts delivered daily on time. This upward trend demonstrates the boost given by coopetition practices in enhancing operational responsiveness, a critical component of the BIM.4D. However, the coefficient of determination (R^2 = 0.2481) suggests that this linear model explains approximately 24.81% of the variability in on-time delivery, indicating a moderate but not linear solid relationship between the days and the on-time delivery of parts.

The results indicate that companies involved in the Coopetition Network experienced substantial improvements in on-time delivery performance by transitioning to coopetition practices. The increase from 67.1% to 77.5% highlights the potential of coopetition to significantly enhance operational responsiveness, which is a crucial element in fulfilling the requirements of the BIM.4D. These findings suggest that coopetition practices can play a valuable role in improving project delivery timelines, thereby positively influencing stone manufacturers' contributions to enhance the benefits of BIM.4D.

6.2. Responding to BIM.5D: Enhancing Labor Productivity Through Coopetition

The BIM.5D dimension integrates cost data with the 3D model, enabling comprehensive budget and financial management throughout the project lifecycle.

Under B.P., employing an average workforce of 49.9, the intervenient companies managed a daily shipment of 338.5 parts, establishing an average labor productivity rate of 6.84 per worker. Implementing C.P. enhanced daily output to 415.8 parts on average while maintaining the same workforce size, boosting the KPI_{LP} to 8.72 per worker. This significant increase showcases the positive impact of cooperation on labor efficiency.

To further analyze the data, Figure 3 illustrates daily KPI_{LP} over 54 observations, highlighting in green the consistently higher productivity under C.P. This provides evidence of the potential contribution of coopetition practices in the stone manufacturing companies to improving the benefits of BIM.5D.

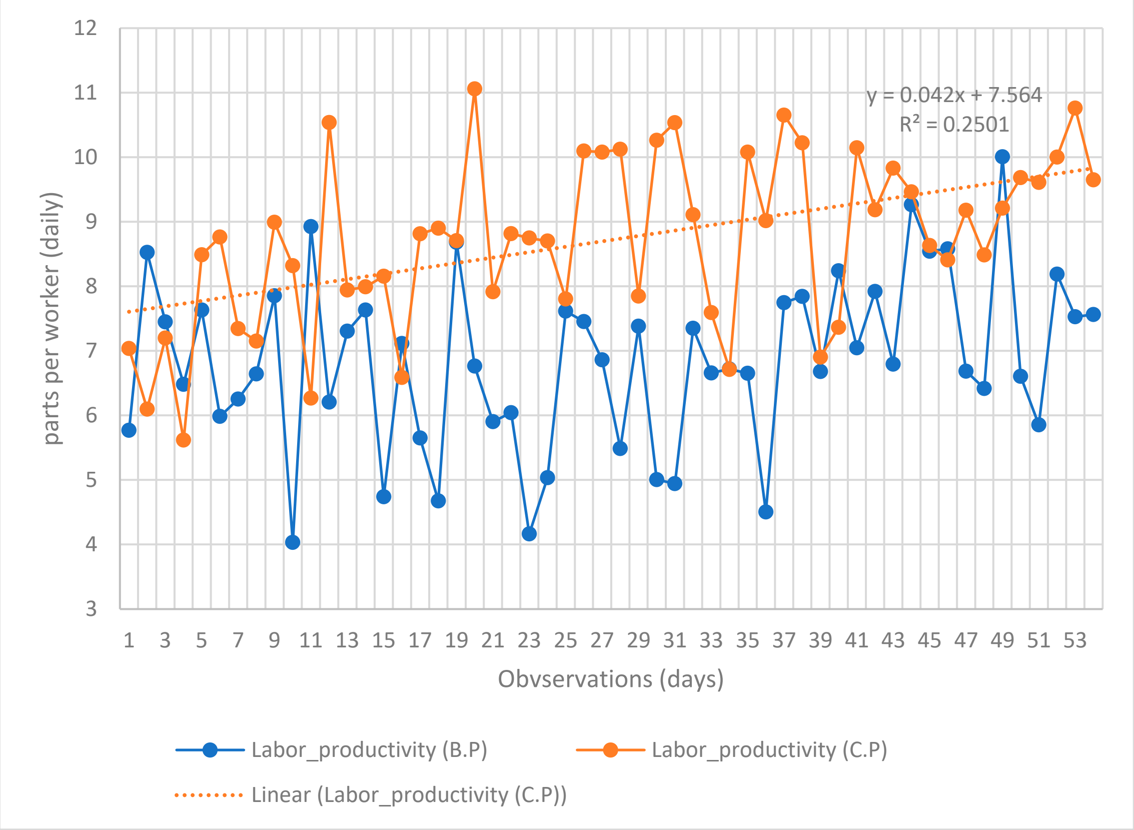

Figure 3. Labor productivity observed daily over 54 days.

The improvement in KPI_{LP} from 6.84 to 8.72 demonstrates how coopetition practices can enhance operational efficiency and cost management. Consequently, stone manufacturers are better equipped to meet the requirements of the BIM.5D, ensuring that projects are completed within budget and on time, leading to improved project outcomes and increased market competitiveness.

6.3. Responding to BIM.6D: CO_2 Emissions Reduction Through Coopetition

The BIM.6D dimension emphasizes sustainability by integrating environmental data into the BIM model to manage and reduce the ecological footprint of construction projects.

To evaluate how coopetition practices assist stone manufacturers in meeting the stringent sustainability requirements of BIM.6D, the $KPI_{CO_2\text{-eq}}$ was employed to measure the environmental impact of energy consumed during production, expressed as equivalent carbon dioxide emissions.

Under B.P, the stone companies recorded an average energy consumption of 4692 kWh per day, resulting in a $KPI_{CO_2\text{-eq}}$ of 3.41 kg CO_2 per part. However, with the implementation of C.P., energy consumption decreased to 4071 kWh per day on average, thereby reducing the $KPI_{CO_2\text{-eq}}$ to 2.68 kg CO_2 per part produced. This represents a 21.8% reduction in carbon emissions per part, underscoring the significant environmental benefits that coopetition practices can deliver.

Figure 4 illustrates the daily CO_2-eq emissions over 54 days, with an apparent reduction in emissions under C.P. highlighted in green.

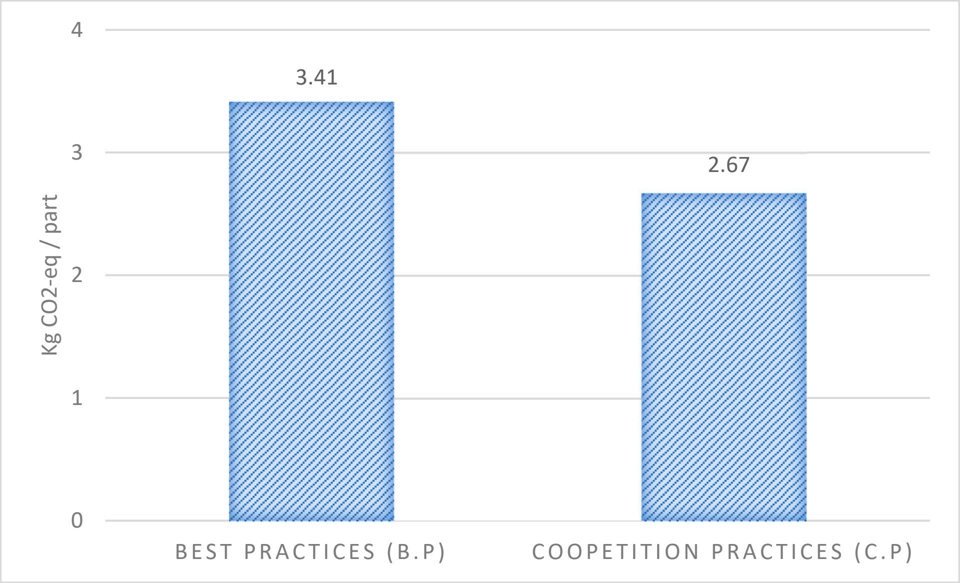

Figure 4. CO_2 emissions reduction achieved through coopetition practices in stone companies.

The improvements in $KPI_{CO_2\text{-eq}}$ demonstrate the potential of coopetition practices to significantly enhance the environmental performance of construction projects. By integrating sustainability considerations into their operations, fabricators can contribute to more sustainable and resilient built environments, aligning with global efforts to combat climate change and promote ecological responsibility.

A *t*-Test and ANOVA were conducted on the emissions data to assess the significance of these improvements. The F-statistic was 2.13, indicating a relatively low value; the *p*-value associated with the F-statistic was 0.1505, which was above the typical significance level of 0.05. This suggests that the regression model does not significantly explain the variation in the dependent variable based on the independent variable.

The analysis indicates that under B.P, the Significance F value (2.15×10^{-8}) indicates that the model is highly statistically significant, meaning the relationship between the CO_2 equivalent under baseline practices and $KPI_{CO_2\text{-eq}}$ is meaningful. In contrast, the F value (0.150532) under C.P suggests that the model is not statistically significant, indicating that the relationship between the CO_2 equivalent under coopetition practices and $KPI_{CO_2\text{-eq}}$ is not meaningful. This shift highlights that the transition from baseline to coopetition practices significantly reduces the impact of the CO_2 equivalent on $KPI_{CO_2\text{-eq}}$, indicating improved environmental sustainability.

However, the intercept is statistically significant, suggesting that the expected value of the dependent variable when the independent variable is zero is approximately 3.075. Despite this, the independent variable does not significantly contribute to changes in the dependent variable. These results suggest a statistically significant difference in environmental performance between B.P and C.P. The transition to coopetition practices has resulted in a significant improvement in sustainability, as evidenced by the reduction in carbon emissions per part.

7. Conclusions

This study addressed the following central question: How can manufacturers enhance their contributions to maximize BIM's effectiveness in the construction industry? By investigating the impact of coopetition practices, this research supports the hypothesis that coopetition can positively influence manufacturers' contributions, thereby enhancing the benefits of BIM in alignment with the United Nations Sustainable Development Goals (SDGs).

Through an Experimental Coopetition Network and a focused case study in the Portuguese ornamental stone sector, the study examined how coopetition affects critical performance indicators such as on-time delivery, labor productivity, and CO_2 emissions. Key findings include the following:

1. On-Time Delivery: This improved from 67.1% under baseline practices (B.P.) to 77.5% under coopetition practices (C.P.) which was a 15.6% increase, reflecting enhanced scheduling and coordination.
2. Labor Productivity: This increased from 6.84 parts per worker under B.P. to 8.72 parts per worker under C.P., a 27.38% improvement, indicating the potential for cost savings and operational efficiency.
3. Environmental Impact: CO_2 emissions decreased from 3.41 kg CO_2-equivalent per part under B.P. to 2.68 kg CO_2-equivalent per part under C.P., a 21.8% reduction, demonstrating a positive environmental impact.

These findings validate the hypothesis within the context of the ornamental stone sector, suggesting that coopetition practices can enhance manufacturers' contributions and optimize BIM benefits. This supports the strategic role of competition in improving project outcomes, increasing competitiveness, and advancing sustainability in the construction industry, especially regarding SDG 11, which promotes sustainable cities and communities.

Practical Implications: The study provides actionable insights for industry professionals and policymakers. For industry practitioners, the observed improvements in scheduling, productivity, and environmental impact indicate that coopetition practices can enhance BIM outcomes and drive operational efficiencies. For policymakers, the findings underscore the potential of coopetition frameworks to foster collaboration and resource sharing within industry sectors, promoting sustainable construction practices and economic resilience.

Limitations and Future Research: While the findings are promising, they are based on a single-sector case study with a limited sample of companies. This scope limits the generalizability of the results across the broader construction industry. Expanding the sample size and including a diverse range of sectors within the construction industry that also utilize BIM would strengthen the representativeness of the findings and further validate the applicability of coopetition practices in varied contexts. Additionally, this study is limited by its cross-sectional design, which captures results at a single point in time. Future research could address these limitations through longitudinal studies that monitor companies over extended periods. Such research will help to determine whether the observed improvements in BIM effectiveness through coopetition are sustained over time or if specific short-term conditions influence them. Expanding the scope this way could also account for technological and contextual variations, providing a more comprehensive understanding of the impact of coopetition on BIM benefits in the construction sector.

Contribution to Theory and Practice: This study advances the theoretical understanding of coopetition by demonstrating its positive impact on BIM benefits and its alignment with SDGs, offering insights into sustainable construction practices. Additionally, the findings contribute a practical framework for implementing coopetition practices to enhance project performance, productivity, and environmental sustainability. These insights offer concrete guidance for industry practitioners and policymakers, supporting a shift towards a more collaborative and sustainable construction sector.

Author Contributions: Conceptualization, A.d.S. and A.J.M.C.; methodology, A.d.S.; software, A.d.S.; validation, A.d.S. and A.J.M.C.; formal analysis, A.d.S.; investigation, A.d.S.; resources, A.d.S.; data curation, A.d.S.; writing—original draft preparation, A.d.S.; writing—review and editing, A.d.S.; visualization, A.d.S.; supervision, A.d.S.; project administration, A.d.S.; funding acquisition, A.d.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by StonebyPortugal, Portaria n.º 43-A/2022 January 19th (Agenda C5—Aviso N.º 02/C05-i01/2022), founded by the Plano de Recuperação e Resiliência, Agendas para A Inovação Empresarial and The APC was funded by Ensinus Estudos Superiores, SA.

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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

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