Article

Advancing BIM and Sustainability with Coopetition: Evidence from the Portuguese Stone Industry

Agostinho da Silva 1,2,* and Antonio J. Marques Cardoso 1

1 CISE—Electromechatronic Systems Research Centre, University of Beira Interior, 6201-001 Covilhã, Portugal
2 CIGEST—Centre for Research in Management, Lisbon Business School, 1700-284 Lisboa, Portugal

* Correspondence: agostinho.antunes.silva@ubi.pt

Abstract: The construction industry plays a crucial role in the global economy but faces persistent challenges such as inefficiency, high costs, and significant environmental impact. Building Information Modelling (BIM) has been proposed as a solution to enhance efficiency and sustainability through digital representations of construction projects. However, the full potential of BIM has yet to be realized. A contributing factor to this gap is that construction manufacturing companies, which produce upstream parts and products used downstream in construction, are often overlooked in discussions of BIM’s benefits. This study explores the potential of coopetition networks to help manufacturing companies better align with BIM dimensions. Coopetition networks, which integrate competitive and cooperative strategies, present a promising method to enhance the effectiveness of manufacturing companies. Focusing on the Portuguese Ornamental Stone industry, the study employs an experimental pilot network facilitated by the Industrial Internet of Things (IIoT) to assess the effects of competition on labour productivity, on-time delivery, and environmental performance among stone companies. The findings indicate that coopetition networks significantly improve alignment with BIM requirements, enhancing operational efficiency and sustainability. Despite being limited by a small sample size, this research offers valuable insights into the role of manufacturing companies in BIM-enhanced construction projects and the broader applicability of coopetition networks in advancing BIM objectives. These results highlight the potential of coopetition networks as a strategic approach to improving performance in the construction industry.

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

1. Introduction

The construction industry is a cornerstone of the global economy, with projected growth expected to exceed USD 4.2 trillion over the next 15 years [1]. Despite its significance, this industry faces persistent challenges, including inefficiency, high costs, prolonged timelines, and substantial ecological impacts [2]. These issues have prompted governments and scholars to advocate for adopting Building Information Modelling (BIM) [3], which promises to enhance efficiency and sustainability in construction by creating comprehensive digital representations of physical and functional characteristics [4].

However, despite intense activity surrounding BIM and its numerous potential benefits, its practical impact has yet to be fully realized [5]. One reason for this gap may be that construction manufacturing companies [6], which are responsible for producing upstream parts and products used downstream in construction, are often overlooked in discussions of BIM’s potential benefits found in the management literature [7].

This oversight results in a significant gap in understanding how construction manufacturing companies operating upstream in the construction process can align their operations to meet the requirements of various BIM dimensions [8]. Given that a specific construction element produced by a manufacturing company impacts the construction project regarding time, cost, and ecological footprint—representing the fourth, fifth, and sixth BIM
dimensions—it follows that to fully realize BIM’s potential, construction manufacturing companies must effectively align their production with these dimensions [9].

A promising approach to addressing current enterprise challenges arising from global digitalization is the concept of coopetition networks [10], which combine competition and cooperation for mutual benefits [11]. Recommended by official entities to respond to the modern challenges faced by SMEs, such as those outlined by the European Union [12], coopetition could be a solution for aligning construction manufacturing company activities with BIM requirements.

Among the various industrial sectors supplying the construction industry, the ornamental stone sector has always been a significant contributor [13]. This sector, primarily composed of SMEs, provides elements for cladding, kitchen tops, and other applications essential for sustainable construction [14]. Can coopetition networks facilitate the alignment of ornamental stone companies with BIM requirements?

To address this question, this study evaluates the potential of coopetition networks to meet BIM requirements within the Portuguese Ornamental Stone industry (OS-PT), a key sector in the national economy [15]. The investigation employs a case study methodology conducted through a coopetition experimental pilot network (CEPN) facilitated by an Industrial Internet of Things (IIoT) artifact to connect the companies involved digitally. The study includes selected companies in the OS-PT sector and aims to determine whether adopting coopetition practices enables these companies to better align with BIM requirements.

Due to cost constraints, the CEPN includes only three OS-PT companies. Despite this limitation, the study’s findings provide valuable insights into the role of construction manufacturing companies in BIM-enhanced construction projects and highlight the potential impact of coopetition networks operating upstream in realizing BIM benefits downstream.

2. BIM as a Potential Response to an Efficient Construction Industry

The construction industry has been criticized for generating avoidable waste, reflected in high costs, extended project timelines, and significant ecological footprints [16]. In response, governments and industry practitioners have supported the gradual implementation of BIM to increase transparency [3] and efficiency [6].

BIM has evolved as a successor to CAD in the construction industry [17]. Driven by government directives, the construction industry is now at the forefront of incorporating BIM into its practices, motivated by cost reduction goals, shortened project timelines, and alignment with sustainability principles [18]. This integration signifies a significant shift towards more responsible and efficient design and construction methodologies [19].

BIM represents a paradigm shift in conceptualizing, executing, and managing construction projects. At its core, it provides a digital twin of physical construction [20]. The essence of BIM technology lies in creating a digital representation that mirrors every facet of physical construction [21]. However, this has led to some confusion in the industry regarding the conflation of BIM maturity level with BIM dimensions [22]. BIM maturity refers to the sophistication level at which the supply chain can exchange information, highlighting the collaborative capabilities of the involved parties. In contrast, BIM dimensions encompass the various data types attached to a model, adding depth and insight into the project’s lifecycle [23].

Incorporating data dimensions within a BIM context allows for unparalleled comprehension of the construction process [24]. Designers and stakeholders gain a holistic view of the project, including initial design, work stages, delivery methods for each component, budgeting, and maintenance plans. These dimensions foster a more refined management approach [25].

While the first three dimensions (3D BIM) relate to the solid geometry of objects, the fourth dimension (4D BIM) integrates the crucial aspect of time, marking a significant evolution in project management and coordination within the construction industry [25]. By incorporating project timelines directly into BIM models, 4D BIM introduces a dynamic
and interactive approach to planning, allowing for real-time visualization of construction sequences [17].

The fifth dimension (5D BIM) focuses on cost management within construction projects by integrating financial data with each component in the digital model [26]. This holistic approach transforms budgeting into a dynamic, detail-oriented process, enabling immediate visibility and ongoing updates on the financial impacts of design choices and manufacturing changes throughout the project’s duration [27].

The sixth dimension (6D BIM) focuses on sustainability by integrating environmental sustainability metrics directly into the building information model [28]. This provides real-time insights into the ecological footprint of materials and processes throughout a project’s lifecycle, equipping professionals with the tools to make decisions that adhere to sustainability objectives [29].

Beyond these, BIM includes other dimensions, particularly maintenance and construction safety, allowing for a holistic view of the process from project inception to demolition [9]. However, to realize the full potential of BIM, construction manufacturing companies must effectively address, contribute to, and meet these BIM dimensions.

A fundamental assumption of this study is that some indicators of construction manufacturing companies—low cost, completion on time, and sustainability—are crucial for realizing the benefits of BIM. This assumption is supported by the existing literature, which explicitly indicates the relevance of these performance aspects.

Cost Efficiency: BIM enables precise cost estimation and budget management (5D BIM), directly linking to the performance aspect of low waste [30]. Manufacturing companies that excel in cost management contribute to more accurate financial planning and control, reducing the risk of budget overruns and ensuring financial efficiency throughout the project lifecycle [26]. By integrating cost data into BIM models, these companies help identify cost-saving opportunities and optimize resource allocation, which is essential for achieving overall project cost efficiency [19].

Timely Completion: Integrating project schedules into BIM models (4D BIM) enhances time management by providing the real-time visualization of construction sequences. Companies that adhere to timelines can leverage BIM to synchronize their activities with other stakeholders, minimizing delays and improving coordination [25]. Effective time management by construction manufacturing companies ensures that project milestones are met, contributing to the timely completion of construction projects and enhancing overall project efficiency [31].

Sustainability: The focus on sustainability in BIM (6D BIM) aligns with the performance aspect of environmental responsibility. Construction manufacturing companies that prioritize sustainable practices can integrate environmental data into BIM models, enabling the assessment of the ecological impact of materials and processes [28]. These companies contribute to reducing the ecological footprint of construction projects, ensuring that sustainability goals are met [32]. Their commitment to sustainability enhances the long-term viability of construction projects and supports industry-wide environmental objectives [33].

By focusing on these three performance aspects, manufacturing companies can significantly facilitate the benefits of BIM at the project level. These performance indicators are not only aligned with the core objectives of most construction projects but are also critical for maximizing the potential of BIM dimensions. Therefore, the adequate performance of suppliers in these three areas plays an important role in enhancing project outcomes, ensuring that BIM’s benefits in terms of cost, time, and sustainability are fully realized.

3. Literature Review

The concept of “coopetition”, initially introduced during the 1980s [34] by Ray Norda, the founder and CEO of Novell, gained prominence in business strategy through the influential work of Nalebuff and Brandenburger (1997). Their work marked a significant shift in understanding competitive dynamics [35]. Over the years, coopetition has
garnered substantial attention within strategic management, evolving through various interpretations and applications [36].

Despite its widespread discussion, the definition of coopetition remains varied, with interpretations spanning different goals, relationships, and organizational contexts [37]. It has been described as a strategy that encompasses the simultaneous pursuit of cooperation and competition among firms, a hybrid activity within the same business entities, and a complex interplay that affects competitive dynamics among different market players [11].

At the nexus of coopetition and networks, a strategic orientation centred around innovation emerges, essential for firms seeking to bridge competitive gaps and effectively manage market challenges [38]. This orientation emphasizes coopetition’s role in navigating competitive terrains and highlights its potential as a catalyst for transformative growth and resilience [10]. Studies show a wide range of findings, underscoring the need for a more unified and in-depth exploration of value co-creation processes in these complex networks [39].

A comprehensive review by Meena, Dhir, and Sushil (2023) reveals that coopetition has been examined through various theoretical lenses, such as Game Theory, Resource-Based View, Paradox Theory, Transaction Cost Theory, and Network Theory [36]. Each perspective, while insightful, often addresses the concept within its specific confines. Regardless of the diversity in definitions, the essence of coopetition converges on the notion of a hybrid relationship where competition and collaboration intertwine to benefit the involved companies [40]. It is particularly relevant in digital supply chains [10].

In the context of manufacturing companies, coopetition is a means to improve efficiency and achieve economies of scale [41]. Specifically, for construction manufacturers, collaboration among competitors holds significant potential, particularly in facilitating the benefits of BIM at the project level [42]. Complex projects require high levels of coordination among various stakeholders, including construction manufacturing companies [43]. Coopetition among these companies can lead to enhanced innovation, better resource utilization, and improved project outcomes. By collaborating on BIM implementation while maintaining competitive drives, companies can share knowledge, reduce costs, and accelerate project timelines [44].

The construction industry faces numerous challenges, such as fragmented supply chains, project delays, and cost overruns [45]. These challenges can be mitigated through effective collaboration and competition among manufacturers, where coopetition becomes highly relevant [11]. By forming coopetitive networks, construction manufacturing companies can integrate their resources and expertise to optimize construction processes [6]. This integration allows for real-time data sharing, improved accuracy in project planning, and more efficient execution of construction activities.

Coopetition in construction manufacturing enhances BIM benefits and fosters a culture of continuous improvement and innovation [42]. When companies cooperate, they can collectively invest in advanced BIM technologies and training programs, leading to higher BIM proficiency across the industry [36]. Simultaneously, the competitive aspect drives each company to strive for excellence, ensuring they remain at the forefront of technological advancements and best practices.

Moreover, coopetition can facilitate the standardization of BIM protocols and practices within the construction industry. Standardization is crucial for ensuring compatibility and interoperability between different BIM systems and tools used by various stakeholders [21]. Through coopetition networks, companies can work together to establish industry-wide standards that streamline BIM adoption and implementation, ultimately leading to more cohesive and successful project outcomes.

The strategic paradigm of coopetition networks represents a powerful approach to harnessing the dual forces of cooperation and competition to foster innovation, enhance competitive advantage, and achieve collective success [11]. This dynamic interplay is particularly intriguing for navigating the complexities of the construction industry and enhancing BIM benefits [27]. Studies have shown that companies can effectively integrate
BIM technologies through coopetition, leading to better project management, reduced errors, and increased efficiency.

4. Methodology

The case study method is invaluable for examining the interface between a phenomenon and its context. It offers a structured approach for event analysis, data collection, and result reporting [46]. This methodology allows researchers to deeply understand the underlying reasons and identify potential future research directions related to the studied instance [47].

Building on the concept of coopetition networks as facilitators of the alignment of ornamental stone companies with BIM requirements, a case study methodology is used to quantitatively assess the contribution of a coopetition network in enhancing BIM dimensions. This quantitative approach provides a structured framework for event analysis, data collection, and result reporting [46], offering a detailed examination of the phenomenon’s interface and context. It also aids in understanding the underlying reasons and identifying potential future research directions related to the case study [47].

To facilitate data collection, the CEPN was implemented in the Portuguese ornamental stone sector, involving a series of sequential steps:

Participant Selection: Stone companies meeting specific criteria were identified and selected for participation. Criteria included technological capability, willingness to collaborate, and relevance to the construction industry.

CEPN Implementation: The selected companies were connected using appropriate technology. A process for data collection was established to ensure real-time data collection and analysis.

Metric and KPI Definition: Metrics and KPIs were defined to evaluate the benefits of coopetition networks in meeting BIM dimension requirements. These metrics focused on time response (4D BIM), price (5D BIM), and ecological footprint (6D BIM).

Data Collection and Analysis: Data on the defined KPIs were gathered through the CEPN by monitoring and recording the performance of the coopetition network in real time. The collected data were analysed to evaluate improvements and gain insights into the effectiveness of coopetition networks in enhancing BIM benefits.

Outcome Evaluation: Assessing the extent to which coopetition networks can facilitate the alignment of ornamental stone companies with BIM requirements.

Outcome Evaluation: assessing the extent to which coopetition networks can facilitate the alignment of ornamental stone companies with BIM requirements.

5. Participant Selection

The Ornamental Stone 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 [48]. Leveraging Portuguese stone, engineering prowess, and generations of accumulated expertise, the OS-PT sector is deeply woven into the fabric of the nation’s identity [49]. As the 21st century progresses, Portugal has solidified its position as a leading producer of stone products, skilfully integrated into the global construction industry, a testament to its competitive edge on the international stage despite the country’s modest geographic footprint [50].

Portugal’s ornamental stone industry, characterized by its vast and varied stone reserves, plays a crucial role in the global market. The shift towards digital collaborative efforts with customers and architects worldwide underscores a dynamic evolution; the sector’s traditional strengths are being repurposed through innovation [15]. This emerging digital engagement, though still developing, is pinpointed as a critical growth avenue for Portuguese stone providers.

According to the Portuguese Stone Federation (2022), the OS-PT sector exports to 116 countries, ranks as the ninth most significant player in the World International Stone Trade, and secures the second position globally regarding international trade per capita.
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 [51].

The strategic implementation of the CEPN began by establishing direct and informal communication channels with the managing directors of potential participant companies. Multiple contacts and evaluations with companies revealed three significant operational constraints.

The first constraint was the limited number of companies with technologically connectable production means. To address this issue, 43 of 661 transforming companies were evaluated in person, of which 23 were pre-selected for having production means technologically connectable to a digital platform.

The second constraint was related to the logistical costs for the research team to operationalize data collection for the CEPN. It was observed that the larger the number of companies involved and the longer the data collection period, the higher the costs involved. Given the budget limitations and the “pilot” nature of the experimental project, it was determined that the CEPN should consist of a network of only three companies, with each data collection period not exceeding 60 days.

The third constraint was the companies’ discomfort with sharing critical data and information. To address this, a comprehensive confidentiality agreement was drafted to protect sensitive information regarding the companies’ operations, clientele, employees, resources, and competitors.

As a result of these trade-offs, three OS-PT companies were formally invited to participate in the study, and the respective confidentiality agreements were signed. To ensure anonymity, the three anonymized companies are designated as “A”, “B”, and “C”.

6. Implementation of the Coopetition Experimental Pilot Network

The emergence of the IoT marks a transformative era, significantly influencing ecosystems through sophisticated sensor technologies that enhance connectivity and data exchange [52]. Building on traditional IoT frameworks, IIoT introduces intelligence to industrial settings, facilitating direct device-to-device communication and supporting the creation of intelligent artefacts that dynamically adapt to user interactions and enhance value co-creation [53]. Empirical evidence highlights the transformative potential of IIoT-based innovations in fostering novel service offerings, such as remote control and predictive maintenance solutions [54]. These capabilities advance operational efficiency and open new avenues for value co-creation within coopetition frameworks, expanding service portfolios and enhancing enterprises’ competitive and cooperative capacities [55].

An example in the OS-PT sector is an IIoT artefact developed through the Inovstone4.0 R&D Project [18]. This IIoT system was designed to connect ornamental stone companies with the digital market [49], refining product specifications and promoting value co-creation between providers and customers, thereby improving customization and operational productivity [56].

The current state of Cockpit4.0 epitomizes the IIoT capacity to redefine market dynamics through direct engagement and collaborative efforts.

Although developing IIoT technology was not within the scope of this research, Cockpit4.0, representing the state-of-the-art in the OS-PT [57], was evaluated as a starting point for transforming the operational technology that facilitates coopetition in the CEPN. This required some additional developments to the artefact. To further harness this potential, new functionalities were added to Cockpit4.0, such as enabling secure connections between competitor firms, resulting in an advanced version called Cockpit4.0+ for this research. This new IIoT artefact, specifically designed to connect rival OS-PT firms, brought enhanced technological capabilities and fostered a collaborative industrial environment conducive to a coopetition network.
OPC-UA (Open Platform Communications Unified Architecture) is a crucial protocol for IIoT because it enables secure and reliable communication between diverse industrial devices and systems [53]. It provides a standardized framework that facilitates interoperability and data exchange across different platforms and manufacturers, essential for the seamless integration of various components in an IIoT ecosystem.

OPC-UA allows different devices and systems to communicate and work together, regardless of their underlying technology. This is vital in IIoT environments where equipment from multiple vendors must interact efficiently [58].

Embedding OPC-UA Cockpit4.0+ bridges gaps in connectivity, efficiency, and responsiveness, fostering an ecosystem where firms thrive through collective innovation and adaptive strategies. Cockpit4.0+ integrates technological innovations like artificial intelligence to promote a collaborative industrial environment, ensuring sustainable operations and maintaining SMEs’ competitiveness in a dynamic market.

Once Cockpit4.0+ was available, even as a prototype, the implementation of the CEPN began. Three companies recognized as leaders in the OS-PT sector were formally connected (Figure 1) in a real cooperation network. These companies could now operate in some domains, like a single factory linked to BIM architects’ stations, regardless of their geographical locations.

![Figure 1. Coopetition experimental pilot network (CEPN).](image)

In each company involved in the CEPN, a Cockpit4.0+ was installed, ensuring secure connectivity between the network companies and capturing potential connections to BIM operators interested in prescribing customized stone on a global scale.

7. Metrics and KPIs Definition

The BIM benefits depend on how each building element meets the requirements of the different BIM dimensions. The 4D BIM requires transparency, accountability, and more effective communication [59] to ensure dynamic on-time delivery. To meet 4D BIM requirements, the stone manufacturers must enhance their scheduling, coordination, and productivity processes, responding positively to the crucial aspect of delivery time [17].

To evaluate this response, the on-time delivery (KPI\textsubscript{OtD}) indicator can be used, as it measures the OS-PT’s ability to consistently meet project deadlines. For this study, KPI\textsubscript{OtD} is calculated as the percentage of stone parts delivered within the agreed timeframe (Equation (1)). Improvements in KPI\textsubscript{OtD} directly enhance the effectiveness of 4D BIM by ensuring timely project execution and adherence to schedules.

\[
\text{KPI}_{\text{OtD}} (\%) = \sum_{i=1}^{n} \left( \frac{\text{parts}_{\text{delivered}_{\text{on\_time}_{\text{daily}}}}}{\text{parts}_{\text{delivered}_{\text{daily}}}} \right)
\]

A 5D BIM integrates cost data with the 3D model, enabling comprehensive budget and financial management throughout the project lifecycle [27]. BIM’s benefits for construction
require that components meet the necessary quality at the lowest cost. Consequently, stone manufacturing companies must respond positively in terms of component cost. For OS-PT to be aligned with 5D BIM, their manufacturing processes must optimize resources to enhance efficiency, using both human and technological resources better to lower waste and costs.

According to the literature on lean management, one way to measure industry efficiency is through labour productivity, which relates output to the labour involved [5]. Therefore, for this study, the indicator for labour productivity (KPI\textsubscript{LP}) has been selected to evaluate the number of stone parts a worker completes within a specified timeframe, indicating the efficiency of labour use (Equation (2)). By enhancing labour productivity, stone companies can better meet the requirements of 5D BIM.

\[
\text{KPI}_{\text{LP}}(\%) = \sum_{1}^{n}(\frac{\text{parts\_produced\_daily}}{\text{workers\_involved\_daily}})
\] (2)

The 6D BIM focuses on sustainability by incorporating environmental data into the BIM model to manage and reduce the ecological footprint of construction projects [29]. This requires manufacturers to use raw materials and processes efficiently to minimize the environmental impact of building materials [60].

To evaluate how a stone company can meet this requirement, the CO2 equivalent (CO2-eq) factor must be considered [61]. This indicator converts the energy consumed into equivalent carbon dioxide emissions, providing a standardized measure of environmental impact. The integration of power networks within the EU makes calculating the CO2 equivalent per country challenging. In Portugal, for example, meeting energy demand during critical periods often requires importing energy produced in other European countries. Therefore, the average European CO2 equivalent factor should be adopted for this case study.

According to the European Electricity Review (2023), the carbon intensity of electricity in Europe varies significantly among different EU member states due to their diverse energy mixes [62]. For instance, countries like Sweden and France have much lower carbon intensities (below 50 g CO\textsubscript{2}/kWh) due to their heavy reliance on nuclear and renewable energy sources [62]. In contrast, countries like Poland and Estonia have higher carbon intensities (over 600 g CO\textsubscript{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\textsubscript{2} per kilowatt-hour (g CO\textsubscript{2}/kWh).

Equation (3) can be used to evaluate the CO2 equivalent (KPI\textsubscript{CO2-eq}) for producing stone parts, reflecting the energy consumed per part produced.

\[
\text{KPI}_{\text{CO2\_eq}}(\text{KgCO2/part}) = \sum_{1}^{n}(\frac{\text{energy\_consumed\_daily}}{\text{parts\_produced\_daily}}) \times 0.276
\] (3)

Reductions in KPI\textsubscript{CO2\_eq} directly impact the construction industry’s CO2 emissions and contribute to the Sustainable Development Goals (SDGs), particularly SDG 11: Sustainable Cities and Communities, by promoting environmentally responsible practices and reducing urban carbon footprints [63].

8. Measuring the Impact of Coopetition vs. No Coopetition

This study evaluates coopetition against scenarios where such interactions are absent (no coopetition). The objective is to understand how coopetition influences the KPIs mentioned above in a manufacturing context. The independent variables considered include Parts Delivered, Parts Delivered On Time, Parts Shipped, Labour Hours Involved, Energy Consumed, and Parts Produced. These variables reflect the companies’ operational efficiency, productivity, and sustainability.
To distinguish between cooperative and non-coopetition scenarios, the study employs a comparative analysis of company outputs during periods of active cooperation and periods when companies operated independently (no cooperation).

This approach evaluated the transition from current practices (CB.P) to a new concept of practices, referred to as coopetition network practices (CN.P), where companies, facilitated by the Cockpit4.0+, share manufacturing resources and raw material stocks to capture market opportunities from BIM users.

The CN.P phase involved structured collaborations among companies, sharing resources, knowledge, and logistics while maintaining competitive aspects. Current practices (CB.P) refer to the no-coopetition phase, a period when companies operate without such collaborative interactions, relying solely on their internal capabilities and strategies.

The independent variables were measured as follows:

- **Parts Delivered**: The total number of parts delivered to customers during the observation period.
- **Parts Delivered On Time**: The percentage of parts delivered within the agreed-upon time frame, reflecting the companies’ ability to meet deadlines.
- **Parts Shipped**: The total number of parts shipped out, indicating the companies’ logistical and production capabilities.
- **Labour Hours Involved (h)**: The total labour hours expended in production provide insight into workforce efficiency and productivity.
- **Energy Consumed (kWh)**: The total energy consumed during production, which is critical for assessing sustainability and energy efficiency.
- **Parts Produced**: The total number of parts manufactured during the period, reflecting overall production output.

The study acknowledges that the outputs of the companies could be influenced by other factors, such as time lapses or learning effects. To isolate the impact of coopetition, these potential confounding factors were controlled by comparing performance metrics during similar time periods and by normalizing data to account for seasonal variations or other external influences. This approach helps ensure that the observed differences in performance metrics can be more confidently attributed to the presence or absence of coopetition.

Coopetition, as a strategic approach, can be considered a latent (hidden) variable that influences the observed outputs. This study operationalizes coopetition through structured interactions between companies, such as joint resource utilization, shared logistics, and coordinated production schedules. By comparing the independent variables under coopetition and non-coopetition scenarios, the study aims to reveal the underlying effects of coopetition on operational performance.

To strengthen the analysis, additional qualitative insights were gathered from company management and operational staff to understand the nature and extent of competition during the study period. This helped contextualize the quantitative findings and provided a clearer picture of how coopetition practices were implemented and their perceived impact on company performance.

### 9. Data Collection and Analysis

A data collection strategy was implemented across two fifty-four-day intervals to assess how coopetition networks influence the selected KPIs.

The first 54-day period, conducted in June and July 2023, was focused on capturing current best practices at the anonymized companies. This baseline phase documented each company’s reliance on internal resources for production and delivery, providing essential reference data for subsequent comparisons. Table 1 presents a summary of the average data collected under CB.P.
Table 1. Summary of average data collected under CB.P.

<table>
<thead>
<tr>
<th>Data ID</th>
<th>Description</th>
<th>Current Practices (CB.P)</th>
<th>Data (Average Daily)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data 1</td>
<td>Parts Delivered</td>
<td>parts_delivered</td>
<td>339</td>
</tr>
<tr>
<td>Data 2</td>
<td>Parts Delivered On Time</td>
<td>parts_delivered_on_time</td>
<td>240</td>
</tr>
<tr>
<td>Data 3</td>
<td>Parts Shipped</td>
<td>parts_shipped</td>
<td>338.5</td>
</tr>
<tr>
<td>Data 4</td>
<td>Labours Involved (h)</td>
<td>labour_involved</td>
<td>49.3</td>
</tr>
<tr>
<td>Data 5</td>
<td>Energy Consumed (kWh)</td>
<td>energy_consumed producing parts</td>
<td>4692</td>
</tr>
<tr>
<td>Data 6</td>
<td>Parts Produced</td>
<td>parts_produced</td>
<td>369.9</td>
</tr>
</tbody>
</table>

The second 54-day period, concluding in November 2023, assessed the effects of integrating the same three OS-PT firms into a CEPN. During this period, the three Cockpit4.0+ systems installed in the companies shared real-time information about the availability of manufacturing resources and raw material stocks. Table 2 presents a summary of the average data collected under CN.P.

Table 2. Summary of average data collected under CN.P.

<table>
<thead>
<tr>
<th>Data ID</th>
<th>Description</th>
<th>Coopetition Practices (CN.P)</th>
<th>Data (Average Daily)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data 7</td>
<td>Parts Delivered</td>
<td>parts_delivered</td>
<td>454</td>
</tr>
<tr>
<td>Data 8</td>
<td>Parts Delivered On Time</td>
<td>parts_delivered_on_time</td>
<td>358</td>
</tr>
<tr>
<td>Data 9</td>
<td>Parts Shipped</td>
<td>parts_shipped</td>
<td>415.8</td>
</tr>
<tr>
<td>Data 10</td>
<td>Labours Involved (h)</td>
<td>labour_involved</td>
<td>49.3</td>
</tr>
<tr>
<td>Data 11</td>
<td>Energy Consumed (kWh)</td>
<td>energy_consumed producing parts</td>
<td>4071</td>
</tr>
<tr>
<td>Data 14</td>
<td>Parts Produced</td>
<td>parts_produced</td>
<td>416</td>
</tr>
</tbody>
</table>

Data management and privacy were 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 as detailed in the methodology section. This ensured a secure and consistent approach to data handling, enabling detailed analysis while safeguarding the privacy and proprietary information of the participating companies.

Table 3 shows the assessment of KPIs for both CB.P and CN.P. It illustrates the quantitative gains achieved through the implementation of coopetition practices.

Table 3. Assessment of KPIs for CB.P and CN.P.

<table>
<thead>
<tr>
<th>Key Performance Indicators (KPIs)</th>
<th>CB.P</th>
<th>CN.P</th>
<th>Quantitative Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>KPI—On-Time Delivery (parts/parts)</td>
<td>0.671</td>
<td>0.775</td>
<td>15.6%</td>
</tr>
<tr>
<td>KPI—Labour Productivity (parts/worker)</td>
<td>6.84</td>
<td>8.72</td>
<td>27.38%</td>
</tr>
<tr>
<td>KPI—CO2-eq (KgCO2/part)</td>
<td>3.41</td>
<td>2.68</td>
<td>21.8%</td>
</tr>
</tbody>
</table>

Based on these data, the following section focuses on interpreting the results to determine whether a coopetition network can positively impact stone companies’ response to BIM requirements. This interpretation will draw conclusions about the effectiveness of coopetition networks as facilitators in aligning ornamental stone companies with BIM requirements.

10. Outcomes Evaluation
10.1. Meeting the 4D BIM Requirements through Coopetition Networks

The 4D BIM integrates the crucial aspect of time, significantly advancing project management and coordination within the construction industry. By incorporating detailed
scheduling and time-related data into the BIM model, 4D BIM enables real-time visualization of construction sequences, improves planning accuracy, and enhances the ability to foresee and mitigate potential delays. This dynamic approach ensures that projects stay on schedule, fostering greater transparency, accountability, and communication among all stakeholders.

To evaluate how coopetition networks help manufacturing companies meet the requirements of 4D BIM, the KPI\textsubscript{OtD} was assessed to determine the manufacturers' gains when they evolve from CB.P to CN.P. From the data collected, under CB.P, the KPI\textsubscript{OtD} was recorded at 67.1%, with 240 out of 339 stone parts delivered as scheduled. Conversely, CN.P significantly increased the KPI\textsubscript{OtD} to 77.5%, with 358 out of 454 parts delivered on time.

Examining the on-time delivery trend during the observation periods, Figure 2 depicts the percentage of deliveries made on time each day, offering insights into the consistency and reliability of delivery services over the observed period.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{Trend in on-time delivery over 54 daily observations.}
\end{figure}

The trend in KPI\textsubscript{OtD} over 54 daily observations is described by the linear equation shown in Figure 2, representing the number of stone parts delivered on time, and \( x \) represents the day number. The positive slope of 1.8352 indicates a gradual increase in the number of parts delivered daily on time.

From these results, the companies involved in the CEPN experienced substantial improvements in on-time delivery performance by transitioning to CN.P. The increase from 67.1% to 77.5% demonstrates the potential of coopetition networks in enhancing operational response in time, which is a critical component of the 4D BIM dimension. Despite these positive gains, the coefficient of determination (\( R^2 = 0.2481 \)) suggests that this linear model can explain approximately 24.81% of the variability in on-time delivery, suggesting a moderate but not linear solid relationship between the days and the on-time delivery of parts.

Although these findings are promising, a statistical test is needed to evaluate whether CN.P makes a significant difference compared to CB.P. A t-test is an appropriate method for determining if there is a significant difference between the means of two groups. It assesses whether the observed differences in the sample data can be generalized to the population. The test produces a p-value, indicating the probability that the observed differences occurred by chance. A p-value less than a chosen significance level (commonly 0.05) suggests that the differences are statistically significant.
In this analysis, considering that the two datasets, CB.P and CN.P, come from the same universe and are paired, a paired t-test was used. The t-test applied to the datasets CB.P and CN.P resulted in a p-value of $23.92 \times 10^{-15}$.

This low p-value indicates that the probability of observing the difference in means by random chance is exceedingly small, suggesting a highly significant difference between the on-time delivery performance of CB.P and CN.P. Therefore, it can be concluded that the transition to CN.P has resulted in statistically significant improvements in on-time delivery performance.

Under CB.P, the regression model is statistically significant (Significance F = 0.002502), indicating that the relationship between on-time delivery and KPI\textsubscript{OtD} is meaningful. In contrast, under CN.P, the regression model is not statistically significant (Significance F = 0.612009), suggesting that the relationship between on-time delivery and KPI\textsubscript{OtD} under coopetition practices is not meaningful. This indicates that the performance of KPI\textsubscript{OtD} under coopetition practices requires ongoing monitoring, with necessary adjustments to ensure that the shift from current best practices results in actual performance improvements. To fully realize the potential benefits of coopetition, it may be necessary to revisit and refine network practices by enhancing communication, setting clearer goals, and offering better incentives for cooperation.

10.2. Meeting the 5D BIM Requirements through Coopetition Networks

The 5D BIM dimension integrates cost data with the 3D model, enabling comprehensive budget and financial management throughout the project lifecycle. This integration allows for more accurate cost estimation, efficient resource allocation, and continuous cost monitoring. By providing a detailed financial overview linked to the 3D model, 5D BIM helps stakeholders make informed decisions, identify potential cost overruns early, and implement cost-saving measures effectively.

To evaluate how coopetition networks help manufacturing companies meet the requirements of 5D BIM, the KPI\textsubscript{LP} was assessed to determine the gains from CB.P to CN.P.

Under CB.P, employing an average workforce of 49.9, the OS-PT companies managed a daily shipment of 338.5 stone parts, establishing a labour productivity rate of 6.84 parts per worker. Implementing CN.P enhanced daily output to 415.8 stone parts while maintaining the same workforce size, boosting the KPI\textsubscript{LP} to 8.72 parts per worker. This significant increase showcases the positive impact of competition on labour efficiency.

To examine the averages more closely, Figure 3 illustrates daily KPI\textsubscript{LP} over the 54 observation days, highlighting in green the consistently higher productivity under CN.P. This provides clear positive insights into the potential contribution of coopetition networks to improving the benefits of BIM.

The improvement in the KPI\textsubscript{LP} from 6.84 to 8.72 highlights the ability of coopetition networks to enhance labour productivity. This improvement suggests that stone companies can better meet the requirements of 5D BIM. Increasing productivity makes projects more likely to be completed within budget, enhancing project outcomes and greater market competitiveness.

A paired t-test was conducted to evaluate the difference in labour productivity between the two datasets, CB.P and CN.P. Since both datasets are derived from the same universe, they are naturally paired. The t-test yielded a p-value of $1.7729 \times 10^{-9}$, indicating that the transition to CN.P has led to statistically significant improvements in labour productivity.

Under CB.P, the ANOVA Significance F value of $7.4 \times 10^{-23}$ indicates that the model is highly statistically significant, meaning Labour Productivity under current best practices has a solid and meaningful relationship with KPI\textsubscript{LP}. In contrast, under CN.P, the ANOVA Significance F value of 0.700662 shows that the model is not statistically significant, suggesting that Labour Productivity under coopetition practices does not have a meaningful relationship with KPI\textsubscript{LP}. Given these findings, the performance of KPI\textsubscript{LP} under coopetition practices should be continuously monitored, and adjustments should be made to ensure that the transition from current best practices results in actual performance improvements.
To achieve the intended benefits of coopetition, a thorough reassessment and refinement of these practices may be necessary.

Figure 3. Daily labour productivity across 54 observations.

10.3. Meeting the 6D BIM Requirements through Coopetition Networks

The 6D BIM dimension emphasizes sustainability by integrating environmental data into the BIM process. This integration aims to manage and reduce the ecological footprint of construction projects, promote efficient resource use, minimize waste, and help achieve sustainability goals throughout the project lifecycle. By embedding environmental metrics into the BIM model, 6D BIM provides stakeholders with the tools to analyse and optimize the environmental performance of building materials and processes, ensuring that sustainability considerations are integral to decision-making.

Under the CB.P, the OS-PT companies recorded an energy consumption of 4692 kWh per day, producing a KPI_{CO2-Eq} of 3.41 kg CO2 per part. With the implementation of CN.P, energy consumption decreased to 4071 kWh per day, reducing the KPI_{CO2-Eq} to 2.68 kg CO2 per part produced. This represents an average 21.8% reduction in carbon emissions per part.

The analysis of the 54 observation days of CO2 equivalent emissions, as depicted in Figure 4, shows a reduction in emissions under CN.P, illustrated in green. This demonstrates the effectiveness of coopetition networks in enhancing sustainability performance and contributing to the goals of 6D BIM.

A t-test was conducted on the emissions data to assess the significance of these improvements. The t-test yielded a p-value of 7.96775 \times 10^{-8}.

This result suggests a statistically significant difference in environmental performance between CB.P and CN.P. Therefore, it can be concluded that the transition to coopetition networks has resulted in a significant improvement in sustainability, as evidenced by the reduction in carbon emissions per part.

Under CB.P, the ANOVA Significance F value (2.15 \times 10^{-8}) indicates that the model is highly statistically significant, meaning the relationship between CO2 equivalent under current best practices and KPI_{CO2-Eq} is meaningful. In contrast, under CN.P, the ANOVA Significance F value (0.15032) shows that the model is not statistically significant, indicating that the relationship between CO2 equivalent under coopetition practices and
KPI\text{CO}_2\text{-Eq} is not meaningful. The transition from current best practices to coopetition network practices significantly reduces the impact of CO2 equivalent on KPI\text{CO}_2\text{-Eq}.

Figure 4. Daily CO2_eq emissions across 54 observation days.

11. Conclusions

The findings reveal that coopetition networks have a significant positive impact on OS-PT companies in terms of their labour productivity, on-time delivery performance, and environmental performance, showing that coopetition networks facilitate the alignment of ornamental stone companies with BIM requirements:

On-time delivery: Coopetition network practices improved on-time delivery rates from 67.1% to 77.5%, reflecting enhanced operational efficiency and response times, which are critical for the 4D BIM dimension. The t-test yielded a p-value of $223.92 \times 10^{-15}$, indicating a highly significant improvement and reinforcing the role of coopetition networks in enhancing project execution.

However, the regression analysis under CB.P shows a statistically significant relationship between on-time delivery and KPI\text{OtD}, highlighting that on-time delivery directly influences project performance. In contrast, under CN.P, the regression model is not statistically significant, suggesting that despite the improvement in delivery rates, the relationship between on-time delivery and KPI\text{OtD} under coopetition practices could be stronger and more meaningful. This indicates that to fully realize the potential benefits of coopetition, it may be necessary to revisit and refine network practices by enhancing communication, setting more precise goals, and offering better incentives for cooperation.

Labor Productivity: The transition to coopetition network practices increased labour productivity from 6.84 to 8.72, demonstrating enhanced manufacturing efficiency. This potentially leads to reduced costs as required by 5D BIM. The p-value of $1.77297 \times 10^{-9}$ confirms that this improvement is statistically significant, with a very low probability that the observed difference is due to random chance.

However, the correlation analysis presents a more nuanced view. Under CB.P, the ANOVA Significance F value of $7.4 \times 10^{-23}$ indicates that the relationship between labour productivity and KPI\text{LP} is highly statistically significant, meaning that labour productivity under current best practices has a solid and meaningful impact on KPI\text{LP}. In contrast, under CN.P, the Significance F value of 0.700662 shows that the relationship between labour productivity and KPI\text{LP} is not statistically significant, suggesting that despite the observed improvement in labour productivity, it does not translate into a meaningful
impact on KPI LP under coopetition practices. Given these findings, while the transition to coopetition practices has led to an increase in labour productivity, the performance of KPI LP under coopetition practices should be continuously monitored, and adjustments should be made as necessary to ensure that the transition from current best practices results in actual performance improvements.

Environmental Performance: Regarding sustainability, adopting coopetition practices reduced energy consumption from 4692 kWh to 4071 kWh daily. This led to a decrease in the KPICO2-Eq from 3.41 kg CO2 to 2.68 kg CO2 per part produced, representing a 21.8% reduction in carbon emissions, aligning with 6D BIM requirements. The p-value of \(7.96775 \times 10^{-8}\) confirms that this reduction in carbon emissions is statistically significant.

Under CB.P, the ANOVA Significance F indicates that the relationship between CO2 equivalent and KPI CO2-Eq is highly statistically significant, meaning that CO2 equivalent under current best practices has a strong and meaningful impact on KPI CO2-Eq. In contrast, under CN.P, the relationship between CO2 equivalent and KPI CO2-Eq is not statistically significant, indicating that despite the observed reduction in carbon emissions, the impact on KPI CO2-Eq under coopetition practices is not as meaningful.

This suggests that while the transition to coopetition practices has led to a significant reduction in carbon emissions, the KPI CO2-Eq under coopetition practices should be closely monitored, and adjustments should be made to ensure that the shift from current best practices continues to drive meaningful environmental performance.

These findings contribute to the coopetition literature by demonstrating how coopetition networks can drive significant operational improvements in the construction industry, specifically within the Portuguese Ornamental Stone industry. The study provides empirical evidence of how coopetition networks facilitate alignment with BIM requirements, showcasing their potential to enhance the competitive advantage of construction manufacturing companies. By integrating BIM dimensions upstream, coopetition networks help companies achieve better project outcomes in terms of efficiency, sustainability, and overall performance.

Furthermore, this research highlights the strategic value of coopetition as a mechanism for fostering innovation and sustainability in industries where traditional competitive strategies may fall short. The study also underscores the importance of cooperation among competitors as a means of achieving common goals, such as improved BIM compliance, which can lead to broader industry benefits.

Despite the limitation of involving only three OS-PT companies due to cost constraints, the findings underscore the potential of coopetition networks as a viable strategy for achieving BIM objectives. Further research with a larger sample size and across different sectors is recommended to validate these findings and explore the broader applicability of coopetition networks in meeting BIM requirements.

Overall, this study contributes to the growing evidence supporting coopetition networks as a powerful strategy for enhancing efficiency and sustainability in the construction industry.


Funding: This research received no external funding.

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.
33. Smith, P. BIM & the SD Project Cost Manager. Procedia-Soc. Behav. Sci. 2014, 119, 475–484. [CrossRef]
34. Moore, J.F. The rise of a new corporate form. Wash. Q. 1997, 25, 28–33. [CrossRef]
40. Estrada, I.; Dong, J. Learning from experience? Technological investments and the impact of coopetition experience on firm profitability. Long Range Plann. 2020, 53, 101866. [CrossRef]
42. Xie, Q.; Gao, Y.; Xia, N.; Zhang, S.; Tao, G. Coopetition and organizational performance outcomes: A meta-analysis of the main and moderator effects. J. Bus. Res. 2023, 154, 113363. [CrossRef]
50. da Silva, A.; Cardoso, A.J.M. Coopetition with the Industrial IoT: A Service-Dominant Logic Approach. Appl. Syst. Innov. 2024, 7, 47. [CrossRef]
57. Silva, A.; Dionisio, A.; Coelho, L. Improving Industry 4.0 through service science. Int. J. Serv. Sci. 2020, 7, 58. [CrossRef]
58. Bartelt, M.; Kuhlenk, B. Automated production of individualized products for teaching I4.0 concepts. Procedia Manuf. 2020, 45, 337–342. [CrossRef]
61. OECD. *Rethinking Innovation for a Sustainable Ocean Economy*; OECD Publishing: Paris, France, 2019. [CrossRef]


**Disclaimer/Publisher’s Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.