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*Research Paper*

# Boosting Sustainability: R&D Mobiliser Projects in Portuguese Ornamental Stone Companies

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## ABSTRACT

**Purpose**: The Ornamental Stones (OS) industry, tech firms, and universities created a Three-Tier Consortium (TDC) to develop Research&Development Mobilisation Projects (RDMPs) to enhance flexibility and reduce waste. The OS sector seeks this through lean-thinking and I4.0 technology. This study explores the TDC impact on flexibility, production quality, sustainable resource management, and the RDMP's role in the OS industry.

**Methodology:** The study employed Mayring's (2014) theoretical approach to evaluate the sustainability/performance of Portuguese OS companies engaged in RDMPs. A systematic literature review assessed the Portuguese OS Small and Midsize Enterprises (SMEs) embracing the Industry 4.0 (I4.0) paradigm and technological innovations. Step 1 involved compiling relevant literature; Step 2 systematically analysed articles and company reports detailing the performance of Portuguese SMEs with operating systems.

**Results:** TDC serves as a knowledge-sharing platform for innovation, while RDMP aims to enhance energy efficiency, minimise raw material waste, and boost production flexibility. Portuguese OS companies engaged in RDMP exhibit a 21% improvement rate after adopting modern practices and technologies, reducing environmental impact. Conversely, other companies experienced a negative annual rate of -0.23%.

**Research limitations:** There is a need for more studies due to the novelty of the research topic, particularly regarding the effects of I4.0 and technical innovations from RDMPs on OS companies' performance and sustainability.

**Practical implications:** A framework was developed to help practitioners lead Research and Development (R&D) initiatives and adopt I4.0 technologies within their organisations.

**Originality**: This framework will help to understand how innovation in the RDMPs represents a breakthrough in the OS industry.

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**Keywords:** *R&D Projects; I4.0 Technologies; Ornamental Stone Sector; Innovation; Sustainability; Framework Development.*

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## 1. Introduction

OS are a vital component of Portugal's architectural legacy, dating back to the 15th century. Portugal is a significant producer of high-quality stone products (Siegesmund & Snethlage, 2017), enriching both the domestic construction industry and international markets and thereby enhancing the country's competitiveness (Galetakis & Soultana, 2016) and forecasting commercially viable reserves for 500 years. Stakeholder alliances within the industry strengthen the value chain, align with regional strategies, and foster competitiveness (Breidbach & Maglio, 2016).

However, OS industry sustainability needs a multifaceted approach that combines stakeholder welfare, resource management, and economic viability; despite progress in adopting sustainable practices, such as circular economy principles, challenges persist, mainly regarding the use of finite resources. Thus, initiatives like RDMPs have been developed to drive change in OS industry sustainability amidst evolving challenges. This study addresses the critical issues of sustainable economic utilisation of OS resources, knowledge enhancement in SMEs-dominated sectors and the transformative potential of RDMPs. In detail, the research questions are as follows:

RQ1—How can the sustainable economic value of OS resources be used to increase export capacity and value creation?

RQ2 - How can knowledge of OS resources' economic value be enriched in an SME-driven sector to enable profitable investment, market access, and company cooperation?

RQ3 – Can innovations in RDMPs drive transformative change in the OS industry by improving agility, waste reduction and productivity?

Building on previous research highlighting industry trends and digital advances (DaSilva & Almeida, 2020), this paper emphasises the importance of collaborative efforts and innovative practices tailored to the OS industry's needs (Frazao-I., 2019).

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This study aims to provide empirical evidence of the benefits of collaboration between the Portuguese OS industry, technology companies, and research institutions by identifying relevant RDMPs and technologies and evaluating their implementation in active quarrying and processing operations. The TDC, a networked partnership to facilitate knowledge sharing, emerges as a pivotal catalyst for promoting innovation within the industry. Methodologically, this paper adopts a theoretical approach based on the framework of Mayring (2014) and conducts a systematic literature review following the guidelines of Tashakkori and Creswell (2007). Specifically, the study analyses the efficiency and added value that the development of RDMPs brings, focusing on various dimensions such as manufacturing flexibility, waste reduction and environmental sustainability.

The next paper's sections are as follows: Section 2 provides a theoretical background on the Portuguese OS sector, highlighting its engagement with I4.0 and the importance of innovation, especially RDMPs, for sustainability. Section 3 outlines the OS industry research methodology. Section 4 presents the study's findings, and Section 5 presents the conclusions, limitations, and suggestions for future research.

## 2. Literature Review

### *2.1. The Portuguese Ornamental Stone Sector*

The wealth of a country is closely linked to its resources and how effectively these are utilised to promote economic prosperity and social progress. Portugal, known for its rich natural endowment, has a significant deposit of OS distributed throughout its territory (Carvalho et al., 2013; Frazao-J., 2016), representing one of its most important natural resources in terms of quantity, quality, and diversity. Portugal's historical connection with mineral resources emphasises the country’s importance of stone technology and positions OS as a resource crucial for economic and social development.

The OS sector encompasses a value chain that includes quarrying, extraction, and manufacturing facilitated by modern machinery and tools. The Portuguese Association for Granite and Marble (ASSIMAGRA) reports that the industrial OS cluster generated over 18,800 direct jobs in 2,260 companies, exports to 116 countries, ranks 9th in international trade, is second in international trade per capita, and boasts 823% more exports than imports. Therefore, the OS cluster contributes to private employment in the inland regions and boosts Portugal's international trade. In addition, the growth of the Portuguese OS industry in the

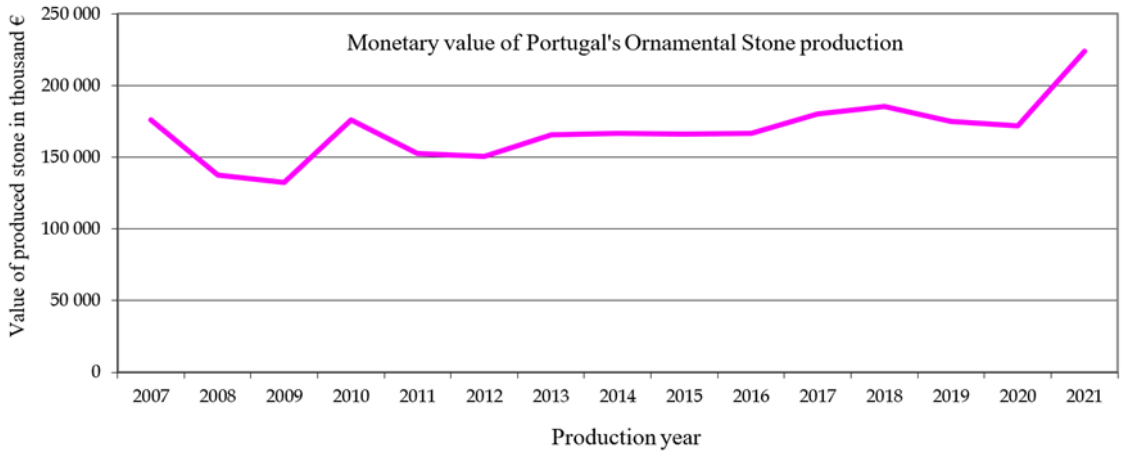
global stone market is driven by the increasing popularity of outdoor activities, rapid urbanisation, and renovation and remodelling projects in emerging economies (Figure 1).

***Figure 1: Main drivers, trends, and markets of the Portuguese OS industry***


*Source: Own Elaboration*

OS demand stems from its advantages in the construction sector, such as increased durability, lower maintenance costs, and reduced environmental impact. With diverse colours and textures, OS are aesthetically pleasing and durable, preferred for renovation projects. Portugal's adaptability to market demands and high-quality raw materials reinforce its position as a key player in the global stone trade.

***Figure 2: Value of OS production volume in Portugal from 2007 to 2021***




*Source: DGEG, 2022 (https://www.dgeg.gov.pt/)*

Remarkably, 45% of exports go to countries outside Europe, contributing significantly to Portugal's economic reputation (Silva, 2014; Frazao-I., 2016), production increase seen in Figure 2.

OS processing plants are tailored to the type of stone being processed and the final product and include sawn slabs, finished slabs, tiles, customised work and other variants (Siegesmund & Snethlage, 2017). Modern processing plants carefully select machines and specifications to optimise workflow. As the stone industry increasingly becomes complex, workflow analysis is crucial in influencing factors like pricing, on-time delivery, quality, performance, scalability, flexibility, interoperability, and reliability (Mashal et al., 2023). Figure 3 illustrates the transition from traditional saws and levers to cutting-edge technology and innovative manufacturing techniques.

***Figure 3: Layout of a Portuguese SME OS processing plant, with improved workflow due to new technology and smart allocation of cutting-edge machinery.***

*Source: Own Elaboration*

Companies can increase productivity with accurate and detailed real-time information about operations. Factors such as stone type, technology, and final product influence the distribution of OS activities (Galetakis & Soultana, 2016). Thus, equipment versatility allows a wide range of materials (Silva et al., 2016).

### *2.2. Background and Key Features of Industry 4.0*

At the 2011 Hanover Trade Fair, the German government adopted a strategic initiative called I4.0 as part of its 'High-Tech Strategy 2020' action plan (Kagermann et al., 2013). This

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initiative shifted the industry, aiming to use various technological advances in products and processes to deliver new value and services to customers and businesses. I4.0 and Smart Manufacturing constitute the fourth industrial revolution, in which technological progress revolutionises production processes (Boyes et al., 2018). The introduction of I4.0 has sparked extensive debate and gained popularity among governments, politicians, and business worldwide (Wiktorsson et al., 2018). I4.0 aims to create a smart industry through autonomous and connected manufacturing technologies (Bai et al., 2020). This paradigm shift will (i) connect factories to the Internet to increase efficiency and intelli-gence (Drath & Horch, 2014) and (ii) significantly change current industrial practices and impact the design, operation, and transport of raw materials and products (Raut et al., 2020).

Within I4.0, manufacturers, suppliers, and customers will be integrated into a virtual value chain. Complete digitalisation makes this new level of collaboration possible, contrasting with the third industrial revolution (Bosi et al., 2020). Accelerated industrial digitalisation aims to meet changing customer demands and enable mass customisation, which requires flexible and agile production structures (Zarte et al., 2022). However, this level of flexibility cannot be achieved with conventional automation. Therefore, modular factory structures consisting of Cyber-Physical Systems (CPS) networked in Internet of Things (IoT) are crucial for overcoming rigid planning and manufacturing processes (Mrugalska & Wyrwicka, 2017). Thus, interoperability between automation technology providers is vital for the of highly modular factory structures success, requiring coordinated standardisation measures.

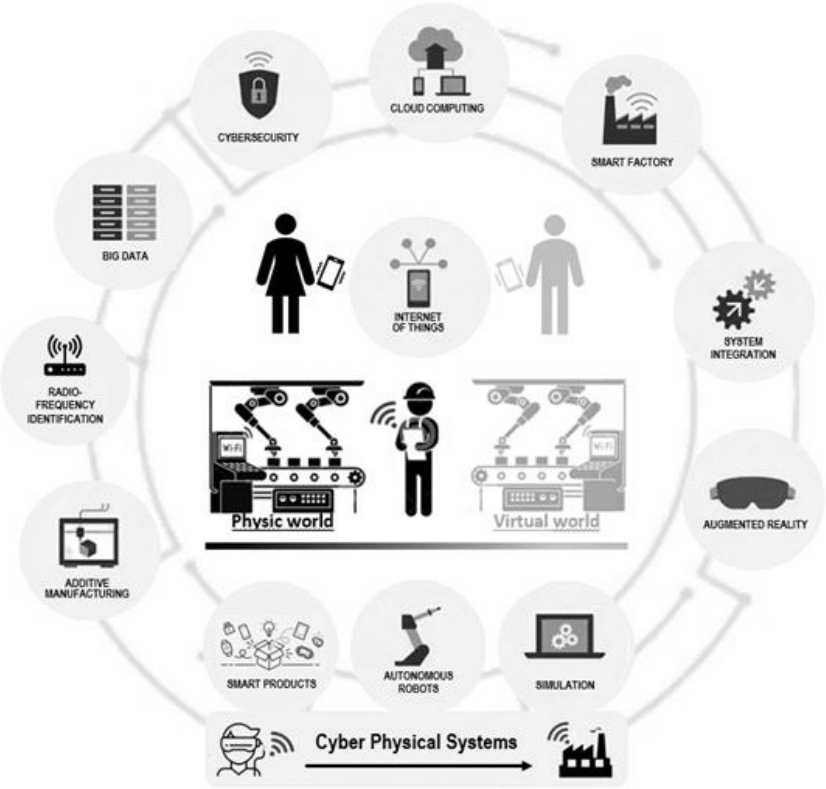
The products evolve from co-created digital DNA (term used to describe the unique digital footprints left by individuals and organizations in the digital realm. Its meaning has since broadened to include a wider range of digital elements, reflecting the increasing complexity and diversity of our digital landscape) (Diniz et al., 2015) to smart objects (Wang et al., 2015) and, finally, physical products delivered to consumers (Luo et al., 2023). This model involves virtual labs where customers co-create, followed by digital manufacturing using Big Data and Cloud Computing (Ivanov et al., 2016). These technologies enable scalable computing power to store and analyse data, improving system performance, saving energy, and optimising operations from design to distribution (Bahrin et al., 2016). Additionally, employees can access these technologies remotely using tablets or smartphones.

I4.0 facilitates machine networking on the factory floor and enables flexible and responsive systems that interact with human instructions and sensory input during manufacturing (Faller & Feldmüller, 2015). Some companies have converted their operations to the I4.0 concept

to achieve production flexibility, leading to mass customisation (Pech & Vrchota, 2022). Switching to digital manufacturing processes is the next stage in industrial value chain organisation and management. Companies must, however, be aware of the potential risks associated with I4.0, such as cyber-attacks, data breaches, and system outages (Algarni et al., 2021).

To embrace sustainability and competitiveness, companies must leverage I4.0's impact on the industrial and service sectors (Smith et al., 2016). This led to the emergence of Digital Factories connected to the IoT (Ivanov et al., 2016). Maximising efficiency and flexibility in these factories are crucial, aided by simulation tools that mitigate risks associated with innovative methods and real-time physical experimentation (Caggiano et al., 2015). While each company's transition to I4.0 is distinct, shared knowledge of relevant technologies and concepts should facilitate interoperability within global value chains (Bosi et al., 2020; Gupta et al., 2020; Pandl et al., 2020). These technologies include IoT, Advanced Robotics, CPS, Big Data, Additive Manufacturing, Cloud Computing, Information Technology, Artificial Intelligence, Augmented Reality, Sensors, Mobile Devices, and Blockchain. Figure 4 provides a framework for I4.0-related technologies, encompassing various concepts crucial for implementation.

***Figure 4: Main drivers, trends, and markets of the Portuguese OS industry***



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*Source: Own Elaboration*

Those above smart objects (Li et al., 2018) or the sensory network connected to the products and means of production embedded in CPS sends, receives, transmits, and processes information through autonomous decisions based on digitisation and previous simulations of product models (Silva et al., 2020).

Integrating sensors, expanding communication networks, and advancements in intelligent robotics and Big Data analysis can potentially revolutionise European production and marketing (Huxtable & Schaefer, 2016). This digital industrial revolution promises enhanced production flexibility, mass customisation, speed, quality, and productivity (Davies, 2015). For instance, companies can reduce machine failures and downtime by 50% and increase production by 20% through advanced analytics in maintenance programs (Davies, 2015). As part of this transformation, industrial companies are evolving into digital entities, enhancing product functionality through digital interfaces and data-driven services and collaborating within industrial digital ecosystems (Bakhtadze & Suleykin, 2021). To realise the benefits of I4.0, efficient data generation, data analysis, and communication will be crucial (Bakhtadze & Suleykin, 2021).

### *2.3. Sustainability, I4.0, and Innovation in the Portuguese OS Industry*

Sustainable economies require equitable production and consumption practices across sectors. With increasing industry competition, optimising production costs, enhancing quality, and shortening lead times are imperative. Organisations emphasise practical strategies to boost performance, accuracy, reliability, decision-making, control, and flexibility. Moreover, the manufacturing sector integrates closed-loop resource utilisation into supply chains to support sustainable operations management decisions.

Our reliance on mineral-derived products spans various sectors like construction, pharmaceuticals, and cosmetics (Azapagic, 2004). However, the extensive OS extraction has raised sustainability concerns, urging stone sector managers to confront new realities. Assessing these impacts has become pivotal, particularly in the circular economy era (Careddu et al., 2018). Waste management from extraction and processing plants poses a significant challenge, along with issues related to critical and secondary raw materials (Dino

et al., 2018). Non-compliance with environmental and legal standards can erode company value and lead to environmental or safety breaches.

The stone industry has a critical and visible impact on the environment, often leading to significant consequences as it affects sensitive areas. These consequences can manifest in destroying habitats, losing fertile land and historically significant archaeological sites. In addition, waste reduction and management pose significant challenges for the stone industry, as companies have a social responsibility to protect the environment and sustainably use natural resources.

For countries like Portugal with advanced OS industries, the disposal of parts during stone manufacturing creates environmental and economic challenges (Carvalho et al., 2018; Rebelo et al., 2019; DaSilva & Almeida, 2020). Additionally, intricate designs hamper production efficiency and are time-consuming.

The construction industry is growing in favour of using natural stone products (as previously presented in Figure 2). This trend is driven by consumers' preference for modern designs with a sense of authenticity. Consumers are increasingly willing to pay more for stone products' natural and long-lasting aesthetics (Bloch, 1995). Consequently, companies must adapt to evolving customer demands as an integral part of their business strategy and find ways to fulfil them more efficiently than their competitors.

Moreover, growing environmental consciousness among consumers and transparent value chain processes underscore the need for a globally connected OS industry capable of embracing sustainability and innovation (Breidbach & Maglio, 2016). Such networks leverage pooled resources and capabilities, enabling companies to achieve synergistic outcomes that would be unattainable individually. Success hinges on prioritising the analysis and development of meticulously designed activities (DaSilva & Gil, 2020) that integrate physical, digital, and biological systems into an intelligent production network where components harmonise seamlessly.

The advanced stages of I4.0 enable the establishment of smart factories, where interconnected machines share real-time data, fostering sustainable operations in OS manufacturing (DaSilva & Gil, 2020). Particularly significant for predominantly family-owned SMEs in the Portuguese OS cluster, these technological advancements offer a competitive edge against market challenges. However, despite achieving sustainable production through innovative technologies, SMEs in the Portuguese OS sector encounter

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hurdles like limited financial backing, inadequate infrastructure, and a need for more expertise in modern technologies. Moreover, they face stiff competition from large multinational corporations, enjoying advantages in market dominance, supply chain accessibility, and service quality.

Undeniably, obstacles in I4.0 (I4.0) hinder SMEs' implementation of sustainable production practices. These barriers are interlinked and often have a causal relationship. Therefore, it is essential to identify and remove these barriers through cooperation, distribution, and sharing of company resources. Khanzode et al. (2021) conducted a study on SMEs to identify critical barriers to implementing I4.0 for sustainable production. Their results revealed eight significant barriers (see Figure 5), which coincide with the main difficulties and concerns already expressed by Portuguese SMEs in the OS sector (ASSIMAGRA, 2014; Frazao-I., 2016). "Technological upgrading" and "Lack of government policy" were the two main barriers. However, the authors emphasised that issues such as "Difficult access to credit" and "Cybersecurity" require more attention to mitigate the barriers effectively.

The success of this emerging industry paradigm through I4.0 technologies, coupled with sustainability goals, could lead to a new economic landscape. While traditional economies focus primarily on business, a sustainable economy emphasises efficiently managing scarce resources. However, the success of SMEs in integrating sustainable business principles into industrial growth depends on overcoming barriers to implementing I4.0. As the business environment becomes increasingly competitive, SMEs need innovative approaches to differentiate themselves. They must seize every opportunity to develop new and innovative smart products enabled by I4.0 technologies and offer highly cost-effective solutions.

Researchers advocate for enhanced competitiveness through novel management models integrating operations into systematic eco-industrial networks (DaSilva & Almeida, 2020). This approach, aiming to leverage synergies from collaborative efforts, echoes the "virtual organisations" concept proposed by Camarinha-Matos and Afsarmanesh (2008), emphasising that isolated efforts yield limited results. A climate-friendly infrastructure is fundamental for climate-resilient development (Ramezani & L. Camarinha-Matos, 2020). Hence, the Portuguese OS industry must embrace the latest models for implementing I4.0 technologies across different phases. This choice will sustain competitiveness and sustainability in the future.

In the OS sector, these models should include Information and Communication Technology (ICT) interfaces (Katzy & Obozinski, 1997) that are updated with the results of digital

technologies, especially those from the Architecture, Engineering and Construction (AEC) sector, such as the Building Information Model (BIM) (Li et al., 2020). Consequently, an operating model to promote sustainable industrial (re)configurations through inter-organisational collaboration proves a viable solution for Portuguese SMEs in the OS sector to overcome obstacles in implementing I4.0 for sustainable production (Silva et al., 2016).

### *2.4. Mobiliser Projects Development in the Stone Sector*

Collaboration is widely recognised as a mechanism for enhancing competitiveness and bolstering survivability, especially in turbulent market conditions (Romero et al., 2009). It is also crucial for addressing industry-related environmental, social, and economic issues. Consequently, cohesion within the stone industry becomes imperative to leveraging sustainable economic value for natural stone (OS) resources and enhancing export capacity and added value.

In 2004, the movement to mobilise the Portuguese OS sector aimed at waste reduction and flexibility improvement, with Technological Innovation Projects in a consortium serving as its primary milestone (Peres & Costa, 2006). Later, in 2009, establishing a Portuguese Mineral Cluster targeting Sustainable Development Project initiatives reaffirmed the necessity to prioritise sustainable management, efficient resource utilisation, and sustainable consumption and production patterns. These efforts materialised through RDMPs within a consortium of companies and encountered the challenge of nurturing trustworthy and increasingly sustainable entities regarding health, safety, and environmental standards.

Critical questions warrant consideration. Over the past 17 years, has the consortium achieved the objectives of the Portuguese OS sector's mobilisation movement? Has it been done by promoting knowledge and sustainable economic valuation of mineral resources, enhancing export capacity, or promoting R&D, technologies, and innovation? Alternatively, has it focused on improving conditions for productive investment, market access, and skill enhancement (technical, technological, and managerial), along with fostering inter-company and inter-institutional cooperation? Also, what strategies have contributed to the success of the consortium? These concerns align with the initial questions that initiated this review.

## 3. Methodological Approach and Related Outcomes

This paper aims to establish exploratory research that justifies a Portuguese business policy for the OS sector, supported by a collaborative operating network within the paradigm of

I4.0 technology. The review methodology seeks to explore the potential business interests and impacts of gradually adopting RDMPs to foster innovative practices, incorporate new technologies, and embrace lean thinking methodologies within Portuguese OS SMEs to enhance industry competitiveness.

The study adopts a theoretical (non-empirical) approach as outlined by Mayring (2014), conducting a semi-systematic literature review to evaluate the performance and sustainability of Portuguese OS SMEs. Semi-systematic literature reviews, as recommended by Mayring (2014) and emphasized by Snyder (2019), are crucial for exploring research issues, theoretical considerations, and existing studies. Semi-systematic reviews trace the evolution of knowledge within a field and synthesize diverse approaches through meta-narratives, aligning with our research objectives. Transparency and a clear research strategy are emphasized in this methodological approach to assess the rationale behind judgments.

Our methodological approach focuses on scientific publications that address OS companies embracing the I4.0 paradigm and technological innovations, and the search was conducted using Google Scholar and prominent search portals such as EBSCO Host. Carefully selected search terms were used to capture relevant literature on the performance and sustainability of Portuguese OS SMEs within the I4.0 paradigm. Data were systematically collected from these databases to ensure a comprehensive exploration of research issues and theoretical considerations. This non-empirical (theoretical) research develops in two stages: Stage 1 involves compiling all relevant literature on OS-relevant constructs, while Stage 2 involves systematically analysing the listed articles that present the performance of Portuguese SMEs with operating systems using a descriptive and interpretive approach.

Since a semi-systematic review methodology has applications in qualitative research, a thematic analysis is employed to analyse and synthesise findings, thereby contributing to mapping the research landscape concerning the impact of TDC on flexibility, production quality, sustainable resource management, and the role of RDMPs in the OS industry.

To ensure methodological rigor, specific criteria were established for article selection, including relevance to the research topic, publication date range (2000-2023), and a focus on Portuguese OS SMEs embracing technological innovations. This approach also aims to elucidate about the impact of I4.0 on the OS-SME cluster. The inclusion of each selected article was based on its contribution to the research objectives and relevance in supporting the arguments presented in this work. In addition, references to supporting studies were

methodologically considered. These studies provide a theoretical base for our research approach and methodology, enhancing the credibility and robustness of our review.

The methodology outlined in this study contributes to advancing the understanding of the impact of RDMPs, and I4.0 technologies on the performance of Portuguese OS SMEs. By employing a semi-systematic literature review approach, we have developed a framework for identifying key indicators and providing recommendations to enhance the performance of these SMEs. This methodology adds value to existing literature by offering a comprehensive analysis of state-of-the-art industry practices within the Portuguese OS sector.

The role of I4.0 technologies as a bridge to sustainable production has become an important research topic in the last decade. Many studies describe I4.0's impact on industry, the economy, and society. Against this background and with a view to the study's objectives, the first methodological step was to conduct a systematic search via Google Scholar. Subsequent investigations were conducted via significant search portals such as EBSCO Host, whereby several databases were searched from this portal. The initial search focussed primarily on studies published between 2000 and 2023. Data were searched and collected from these databases using the key terms listed in Table 1.

***Table I: First approach of database search***

| | **SEARCH-KEY-PHRASES** | | | |
|---|---|---|---|---|
| | I4.0 Industry -4.0 | R&D Mobilising-Projects | Industry -R&D | Ornamental Stone |
| **ACM-Digital Library** | 729 | 0 | 19 | 1 |
| **IEEE-Xplore** | 822 | 0 | 7 | 0 |
| **Emerald-Insight** | 81 | 1 | 17 | 1 |
| **Science-Direct** | 7158 | 30 | 820 | 393 |
| **Springer** | 848 | 0 | 11 | 9 |
| **Web-of-Science** | 1282 | 0 | 173 | 31 |
| **TOTAL** | 10920 | 31 | 1047 | 435 |

*Source: Own Elaboration*

Table 1 results underline the research on I4.0, RDMPs, research, and development in the OS industry sector. The literature selection was refined according to Kiel (2017) guidelines:

1) The time horizon was adjusted twice. Firstly, to cover the period 2004–2023. In January 2004, the Portuguese OS sector noted the need to promote a lean and digital strategic path for OS (Leanstone) by adopting Leanstone technologies and techniques.

2) The time horizon was re-adjusted to cover 2010–2023. Though I4.0 was only creäted in Germany in 2011, 2010 was included for the "mobilisation of projects" and the "OS sector".

3) Focus on international and area-specific databases for managing RDMPs and I4.0.

4) Only research articles and publications in conference proceedings were considered. As I4.0 is still very new, industry reports were primarily used to identify future trends.

5) The publications were filtered based on a keyword search shown in Table 1.

6) The selected publications were filtered (title, abstract and conclusion reviewed).

7) The final selection of publications was subjected to a review. Content analysis was used to search for topics related to I4.0, CPS, IoT, manufacturing systems, automation, control engineering, feature extraction, intelligent manufacturing systems, production engineering, wireless sensor networks, factory automation, project teams, industrial research and development, operating systems, and OS.

The search was then refined to combine the terms shown in Table 2. The dates were also adjusted to 2010–2023. The results highlight the impact of knowledge about digital I4.0 technologies and their use and RDMPs on the Portuguese OS sector. The final set of publications was reviewed, and a content analysis was used to categorise the competencies of the Portuguese OS sector in terms of rapidly reducing raw material waste, transforming efforts into productivity gains, and increasing the ability to respond to market demand driven by RDMPs and I4.0 technologies and innovation trends.

***Table II: Second approach of database search***

| | **SEARCH KEY PHRASES** | |
|---|---|---|
| | ***Industry-4.0*-OR-*I4.0*-OR-*Mobilizing-projects*-OR-*Industry R&D*-AND-*Ornamental stone*** | |
| | **Portugal** | **All-countries** |
| **ACMDL** | **0** | **189** |
| **IEE-Explore** | **1** | **230** |
| **Emerald-Insight** | **0** | **75** |
| **Science-Direct** | **3** | **309** |
| **Scopus** | **2** | **3** |

| | | |
|---|---|---|
| **Springer** | **1** | **239** |
| **Web-of-Science** | **1** | **2833** |
| **Academia.edu** | **4** | **2** |
| **TOTAL** | **12** | **3880** |

*Source: Own Elaboration*

Only research articles were included in the search, which reduced the number of cases. Four final criteria were used to select items for this paper:

1. They had to be written in English, or a translated version had to be available.
2. They had to be related to the Portuguese OS Sector.
3. The article had to have been published between 2010 and 2023.
4. They had to examine any of the constructs under investigation (determine how far I4.0 process optimisation and innovation in RDMPs have advanced the Portuguese OS sector).

Article reference lists were reviewed for publications that may need to be correctly indexed and found via electronic searches. Table 3 summarises the 12 Portuguese studies in the second database search approach referred to in Table 2.

***Table III: A Summarised Literature Review of OS SMEs, R&D, and I4.0***

| # | FRAMEWORKS | METHODOLOGY | REFERENCE |
|---|---|---|---|
| **1** | To-provide-a-framework-to-better-understand the-problems-raised-from-digital-transformation | Quantitative-and-qualitative approaches | (DaSilva-et-al., -2020) |
| **2** | To-assess-the-innovation-outcomes-throughout the-service-process-in-the-I4.0-operations' shift | Theoretical-approach-validated-through-Service-Science-Theory | (Dionísio-et-al., -2020) |
| **3** | To-assess-the-efficiency-&-image-benefits resulting-from-participation-in-R&D-Mobilizing-Projects | Mixed-approach/multiple-cases | (DaSilva-&-Almeida,2020) |
| **4** | Empirical-Framework-conception-via-Service Science-view-&-evaluate-the-I4.0-operations impact-on-the-Time-to-Deliver-products-in-a digital-marketplace-context | Quantitative approach/cases | (DaSilva-&-Gil, -2020) |
| **5** | To-build-an-info-management-framework-of industrial-CPS-&-introduce-2-new-value co-creation-concepts:-(i)-Fingerprint-(a-virtual vehicle-that-carries-structured-information)-and-Cockpit4.0-interactive-identity--between-service-systems-from-cradle-to-cradle | Theoretical-approach-validated-through-the-Service-Science Theory | (Silva-et-al., -2020) |
| **6** | To-assess-the-Leanstone-operations-economic financial-impact-in Portuguese-OS-companies | Mixed-approach-using-companies'-KPIs-and-Innovation-Outcomes | (DaSilva-et-al., -2020) |
| **7** | To-improve-I4.0-using-a-Service-Science-Theory Perspective-on-a-Service-Dominant-Logic-basis | Theoretical-approach-validated-through-the-Service-Science -Theory | (Silva-et-al., -2020a) |

| | | | |
|---|---|---|---|
| **8** | To-conceptualize-a-service-blueprinting-framework-to-map-the-digital-interaction-and-shared-access-to-service-system-resources-in-I4.0-in-OS-SMEs | Theoretical-approach-validated-through-the-Service-Science Theory | (Silva-et-al., -2020b) |
| **9** | To-conceptualize-an-empirical-framework-for-OS-SMEs-to-keep-their-competitive-advantage-of products-customization-in-BIM-standardized procurement-environment | Multiple-case-study-supported-by-the-Service-Science-Theory-Methods | (Silva-et-al., -2020c) |
| **10** | To-develop-a-VBE/VO-model-bridged-with-BIM/I4.0/IoT-and-Service-Science-backgrounds-to-be-applied-to-the-OS-Industry-under-the-Mobiliser-Projects-action | Exploratory-study/multiple-case-study | (Silva-et-al., -2016) |
| **11** | To-outline-a-collaborative-business-model-in-OS-SMEs-enabling-sustainable/green-building-LCA-with-new-collaborative-relationships-among-SC stakeholders/new-forms-of-BIM-procurement | End-to-end-approach/exploratory-research/expert's-focus-group | (Mirnoori-et-al., -2019) |
| **12** | To-provide-a-framework-for-the-sustainable exploitation-of-OS-to-evolve-into-more-robust added-value-chains | Multi-dimensional methodology | (Carvalho-et-al., -2018) |

*Source: Own Elaboration*

## 4. Illustrative Results and Discussion

Three questions guided our review and research:

[RQ1]: How can the sustainable economic value of OS resources be utilised to increase export capacity and value creation?

[RQ2]: How can knowledge of OS resources' economic value be enriched in an SME-driven sector to enable profitable investment, market access, and company cooperation?

[RQ3]: Can innovations in RDMPs drive transformative change in the OS industry by improving agility, waste reduction and productivity?

Considering these questions, the theoretical approach identified the current sustainability and performance of Portuguese OS SMEs that have embraced the I4.0 paradigm and innovation through R&D projects. The results are as follows:

### *4.1. I4.0 and SMEs of the OS Sector*

All four industrial revolutions have enlightened the labour market, forcing individuals and companies to adapt to new working methods, which require acquiring new skills and knowledge. Targeting [RQ1], our results analysis points to the fact that I4.0 makes it easier for companies to improve production by integrating intelligent and automated mechanisms into the industrial environment. This trend offers SMEs in the OS sector numerous

opportunities to increase productivity, efficiency, flexibility, and cost reduction. However, these SMEs face challenges in improving the conditions for productive investment, as confirmed in the reference works listed in Table 3. The business environment is increasingly dynamic and unpredictable, as demonstrated by the impact of the pandemic on the OS sector.

Companies need a new approach to secure their competitive advantages (Ibn-Mohammed et al., 2021). The advent of I4.0 has the potential to fundamentally change the way OS SMEs do business and impact the skills required. Companies operating in a non-connected system risk losing critical competencies, market competitiveness, or profitability (Liu et al., 2021).

### *4.2. Endeavours to leverage OS resources, knowledge, and sustainable economic value*

Frazão-J.'s research (2016) stresses the sector's leverage, which began in 1998 when a study identified essential strategies and the skills required for the stone industry sector to evolve. These include attracting motivated and educated young people, promoting schooling and vocational guidance initiatives among companies, broadening the range of information on labour markets, and improving the image and social representations of the sector and its professions. Our findings highlight the critical importance of strategic initiatives to cultivate a skilled workforce, enhance sector visibility, and improve the overall perception of professions within the OS industry sector. Emphasizing the importance of attracting and nurturing talented individuals, fostering educational programs, and enhancing the sector's image underscores the key pillars essential for sustainable growth and competitiveness.

Building upon this foundation, the forthcoming research question [RQ2] delves into optimizing OS resources' economic value within SME-driven sectors. With this question, we seek to uncover pathways to empower businesses to make informed investment decisions, expand their market reach, and foster collaborative relationships for mutual growth and success. By exploring these options, [RQ2] aims to provide actionable insights to drive profitability, enhance market positioning, and foster a culture of cooperation and innovation within the sector. From the articles on the Portuguese situation (Table 3), it is envisaged that I4.0 will significantly impact SMEs in the stone sector, particularly on working conditions. Our research has shown positive results since 2004 (Frazao-J., 2016). This turn of events is related to the gradual introduction of innovative practices and significant technological developments in information and communications technology, cyber-physical systems, and IoT (Bosi et al., 2020; DaSilva et al., 2020).

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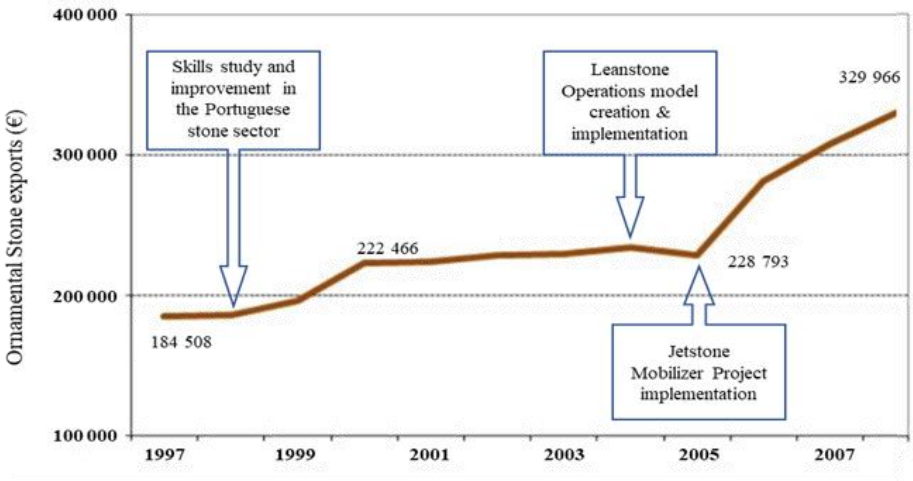
Following the improvements the OS sector implemented due to the 1998 skills and technology study, the 2004 movement emerged to mobilise the Portuguese OS sector, leverage knowledge about reducing waste, and improve flexibility towards a sustainable economic value of OS resources (ASSIMAGRA, 2014; Silva, 2018). According to the Prospective Strategic Study presented by Cluster Portugal Mineral Resources in January 2004 (Silva, 2014), a lean and flexible strategy was required. Innovative technologies conceived according to flexible, lean awareness have led to full innovative development and competitive potential for the OS industry, including OS companies, technology companies, and research centres.

Based on lean practices, the Cluster of Mineral Resources has created an operations model called Leanstone Hornbook, establishing companies' best industry procedures. A company that applies the *Leanstone Hornbook* principles makes its operations Leanstone. Through lean principles, in Leanstone operations, each small increment towards continuous improvement is supported in PDCA (Plan, Do, Check, Action) cycles, continuously repeated until perfection is reached (DaSilva et al., 2020). As a result of adopting this new strategy from 2004 onwards, rising levels of Portuguese OS exports and a growing trade surplus began, positively affecting the OS sector's trade balance, which supports an answer to [RQ2]. Figure 5 shows the evolution of Portuguese OS exports from the first approaches to improving the sector in 1998 to the 2005 impact of the Jetstone project's compliance in OS SME productivity (ASSIMAGRA, 2014, DaSilva & Almeida, 2020). It also considers the aftermath of the first RDMP (Jetstone), which began in 2005.

***Figure 5: Evolution of Portuguese OS Exports after the 1st RDMP (Jetstone)***




*Source: DGEG, 2022 (https://www.dgeg.gov.pt/)*

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According to some authors (Silva, 2014; Dionísio et al., 2020), the challenge in applying the *Leanstone Hornbook* is to ensure that the extraction industry and the processing of raw materials comply with sustainability principles and efficiently manage the OS resources on which the company depends. Thus, research and implementation of innovative approaches involving different stakeholders in the OS sector are crucial to the discussions and the search for solutions (Dionísio et al., 2020a; DaSilva & Almeida, 2020). The movement to mobilise the Portuguese OS sector in 2004 was responsible for the upsurge in RDMP involving all actors in the OS value chain.

### *4.3. RDMPs are drivers to improve the economic potential of OS resources, productive investment, access to markets, and cooperation among OS industry stakeholders*

Addressing [RQ3], results reveal that the development of specific RDMPs, such as *Jetstone Inovstone* and *Flexstone*, embodies the commitment to improve the strength and sustainable competitiveness of the Portuguese OS sector by applying the lean philosophy to technology.

a) RDMP *JETSTONE - 2004-2008 - Development of Automated Systems for the Ornamental Stone Industry*

The first wave of digital technological advancements along the Leanstone trajectory was a pivotal catalyst for establishing the JETSTONE Consortium. This consortium, comprising ten business entities and various academic research centres, gave rise to the RDMP of the same name (Silva et al., 2020a). Among its notable outcomes was the development of several digital lean prototypes validated within factory settings (ValorPedra, 2018). Previous Figure 5 illustrates the surge in OS exports following the inception of the Jetstone consortium in 2005. The Jetstone RDMP bestowed upon the OS sector enhanced flexibility and agility in addressing customised projects, minimising raw material wastage, and enhancing energy efficiency. Consequently, this initiative has bolstered productivity, improved working conditions, facilitated the introduction of novel products and services, and significantly advanced the evolution of the value chain (Frazao-I., 2016; Frazao-J., 2016).

b) RDMP *INOVSTONE 2010-2013 | New Technologies for the Competitiveness of Natural Stone*

The Inovstone project (from June 2010 to December 2013) aimed to develop structured product/process and service (PPS) solutions and equip OS SMEs with technologies. The goal was to promote innovation dynamics at both the product and process levels and facilitate the

development of new products (Mirnoori et al., 2019). This initiative considered the second wave of digital technological development in the Portuguese OS sector, involved a consortium of companies, associations, technology centres and universities. This collaboration enabled the development of eight solutions (PPS) and the validation of fourteen prototypes (ValorPedra, 2018) in a production environment used by several companies. These technological and digital solutions for disruptive innovation were developed to increase productivity and efficiency in OS SMEs. The project produced three innovations, each focussing on process improvement through the integration of new technologies: Innovation in the extraction process, innovation in the valorisation of natural stone and innovation in the valorisation of historic stone (Silva et al., 2016; ValorPedra, 2018). Almost all these advances remain at the cutting edge of technology in the sector. They are consequently used by numerous OS SMEs, thus contributing to the fulfilment of Sustainable Development Goals 9 and 12 (DaSilva & Almeida, 2020).

c) RDMP *FLEXSTONE 2016-2018 | New Technologies for the Competitiveness of Natural Stone*

The Flexstone R&D project has produced the digital technological developments third wave.

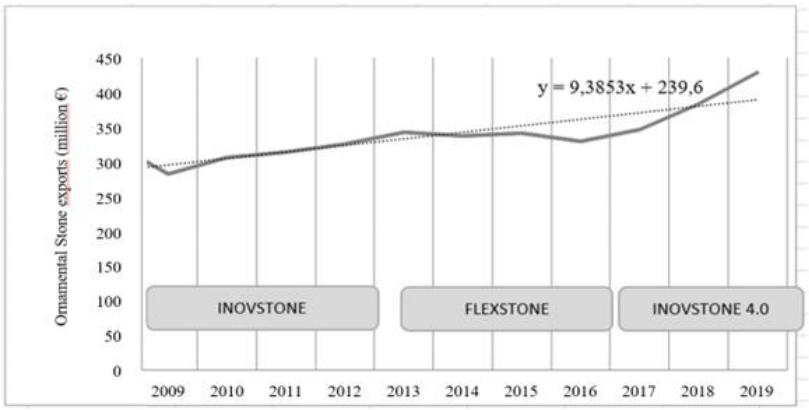
The joint efforts within this project consortium have produced technologies that enable companies in the OS sector to tackle integrated, effective, customised projects of any scale. These technologies help reduce raw material waste, energy consumption, and environmental footprint while significantly increasing productivity. The resulting technological innovations improve companies' operational capabilities and align them closely with I4.0principles.

d) RDMP *INOVSTONE4.0 2017-2020 | Advanced Technologies and Software for Mineral Resources*

The fourth wave of digital technological progress began in 2017 with the initiation of the Inovstone4.0 RDMP (Frazao-I., 2019). This project is about the integration between companies and BIM platforms (Li et al., 2020). The result is several industrial solutions to create shared value in the digital domain and BIM technologies (Frazao-I., 2019; Silva et al., 2016; Silva et al., 2020c). Prototypes developed as part of the Inovstone4.0 project and tested in the industrial environment of SMEs have achieved excellent results. As a result, these technologies are now considered state of the art for OS companies adopting them (Peres & Costa, 2006), representing a significant step towards collaborative manufacturing/smart manufacturing through innovative technological solutions. Inovstone4.0 technologies, focused on co-creating value in digital marketing, especially with BIM users, facilitate

collaboration between customers and suppliers through an increasingly co-creative approach tailored and optimised for business opportunities of any scale. Figure 6 shows the evolution of Portuguese OS exports in line with the successive results of RDMPs (DaSilva & Almeida, 2020; DaSilva et al., 2020; Silva et al., 2020b).

***Figure 6: Evolution of Portuguese OS Exports vs the RDMPs***




*Source: Own Elaboration*

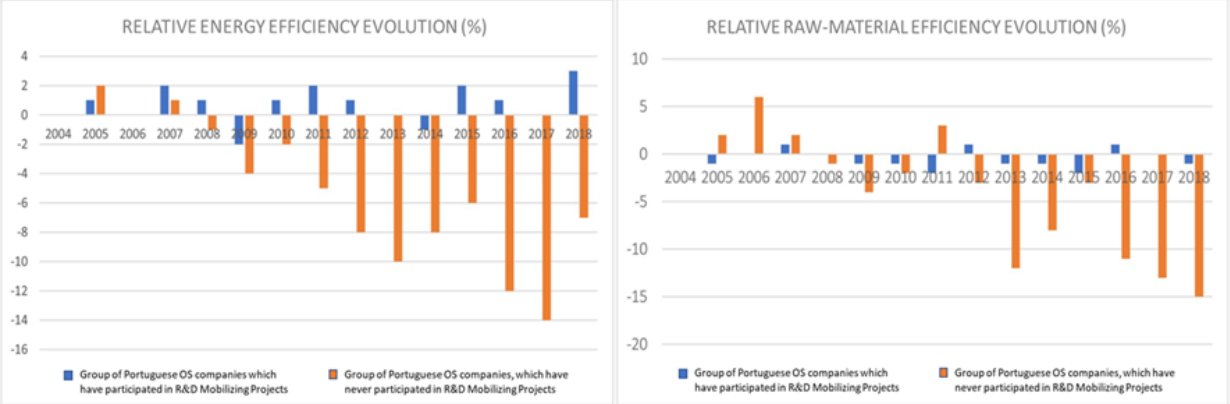
Companies that master these technologies and integrate their operations with BIM platforms are moving towards I4.0 operations (Li et al., 2020; Pandl et al., 2020). Some authors (DaSilva & Gil, 2020; Silva et al., 2016; Silva et al., 2020c) highlight the benefits of using BIM platforms by building designers, mainly architects and engineers, working co-creatively with OS SME stone suppliers. However, not all Portuguese OS companies have adopted *Leanstone* technologies, opting to maintain traditional operational approaches characterised by the absence of digital production machines in the workshops and reliance on communication with the market by phone and email. Frazão-I (2016) concluded that the Portuguese OS companies participating in the Valour Pedra Cluster and voluntarily applying the *Leanstone Hornbook* have made more significant progress in various areas than the industry average over the same period.

### *4.4. RDMPs as drivers for I4.0 Innovation in the OS Industry*

Of the studies in Table 3, several show significant increases in companies implementing *Leanstone Hornbook* in their operations, indicating an increasing digitalisation of their processes. One of these studies (DaSilva et al., 2020) describes and quantifies key performance indicators (KPIs) relevant for assessing the development of efficiency and

image because OS companies participated in RDMPs (e.g. energy efficiency and raw material efficiency, as shown in Figure 7), pointing to an answer to [RQ3].

***Figure 7: Average annual evolution of relative energy and raw material efficiency for OS companies that participated in RDMPs (blue) and those that did not (orange)***

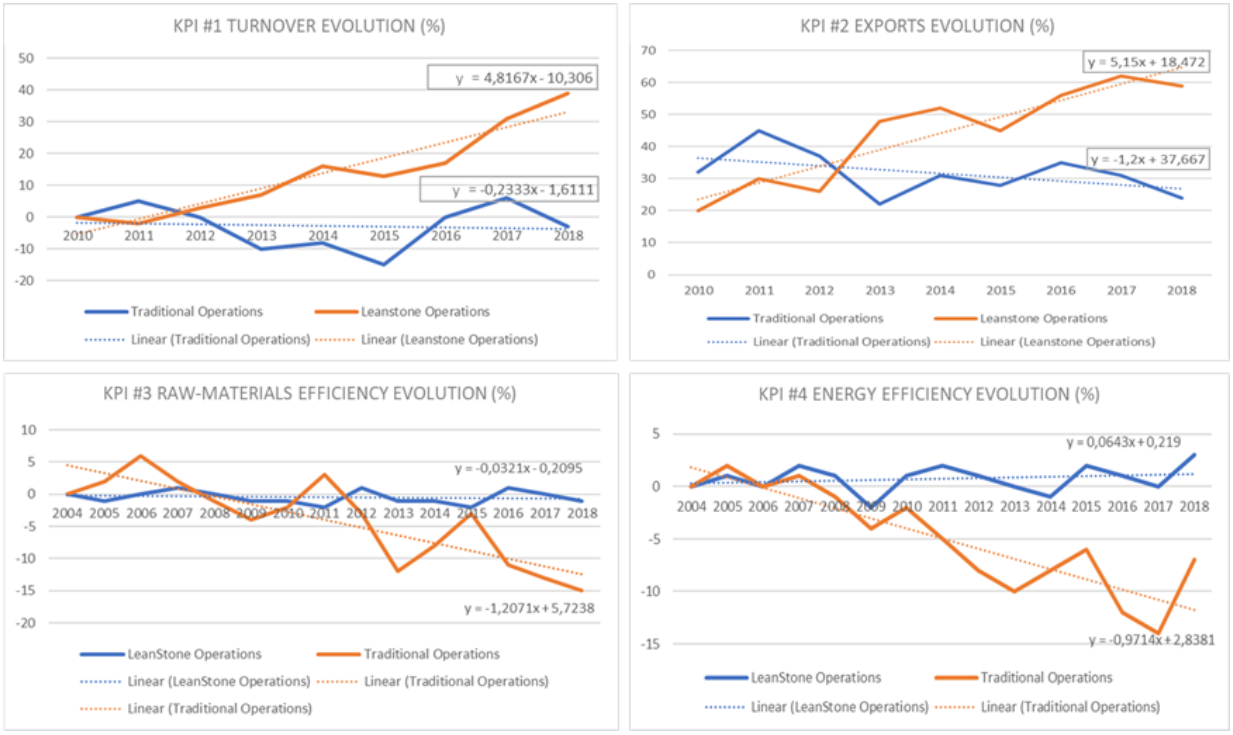



*Source: DaSilva et al., 2020*

Comparing the results with the development and efficiency of companies that have not participated in RDMPs since 2004 reveals remarkable differences and this meet [RQ3]. The Portuguese OS companies show a strong positive response by incorporating modern practices and technologies in their production, allowing them to serve the customisation market. Studies by Frazao-I (2016) and Frazao-J (2016) also address this performance differentiation. DaSilva et al. (2020) point out that the average turnover of OS companies in Portugal that opted for Leanstone in the period 2010-2018 grew at an average annual rate of 4.82%, while the remaining companies recorded a declining trend with an average negative annual rate of 0.23%.

Further research (Dionísio et al., 2020a; DaSilva & Almeida, 2020) shows benefits for companies adopting strategies and technologies from the *Leanstone Hornbook* after assessing and comparing selected KPIs in companies with and without *Leanstone* thinking (Figure 8). These results suggest that within a business model that integrates the digital marketplace resulting from digitalisation thinking and BIM in AEC, this new paradigm could threaten the survival of companies that adhere to traditional activities (Frazao-J., 2016, 2019; Silva, 2018). In this context, where the survival of an important sector for the national economy is at stake, studies (Table 3) point to the digitalisation of companies as the only approach to the BIM paradigm shift in the AEC supply chain (Frazao-J., 2019; Silva, 2018).

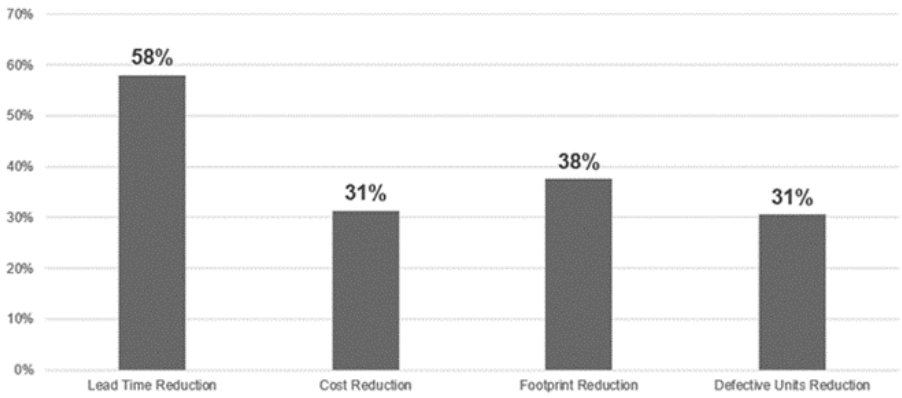
***Figure 8: Evolution of companies following the Leanstone Hornbook with companies following (a) a traditional modus operandi in terms of turnover, (b) exports, (c) the efficiency of raw material consumption, and (d) efficiency of energy consumption***




*Source: DaSilva et al., 2020*

A study based on a mixed methodology indicates significant gains in the OS sector, where companies have shifted their overall operating model to a digital model (I4.0) as part of the Marketing Centre BIM (Frazao-J., 2019; Silva, 2018), as shown in Figure 9.

***Figure 9: Potential efficiency gains of the I4.0 mode of operation in the Portuguese OS sector***




*Source: Silva et al., 2018*

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The research findings underscore the transformative potential of digitalizing business operations in the Portuguese OS sector to enhance SMEs' competitiveness and export capacity. Moreover, the necessary need to adopt BIM to address economic and sustainability challenges in a rapidly evolving global market is emphasized. Looking ahead and following [RQ3], exploring innovations in RDMPs presents an opportunity to drive transformative change in the OS industry by enhancing agility, reducing waste, and improving productivity. By embracing digital transformation and fostering innovation, the OS sector in Portugal stands prepared to not only navigate challenges but also emerge as a market leader in the evolving economic landscape.

## 5. Conclusion

Research, development, knowledge dissemination, and funding of processes and digital technologies supported by CPS are premises set by the European Parliament (Davies, 2015). The European Union believes that I4.0 operations can reverse Europe's industrial environmental impact and industrial decline in recent years. OS companies and managers recognise that linking I4.0 and workers' skills can provide new opportunities for the sustainability of their businesses (Bai et al., 2020; Khanzode et al., 2021). The goals of utilising knowledge and sustainable economic value for OS resources, as well as increasing export capacity and value creation, are becoming critical objectives for the success of companies in the OS sector (RQ1).

The shortening time to market caused by ever-faster technological solutions, the increasing investment costs caused by technological innovations and the increasing complexity of both solutions and technology are reasons to pursue OS SMEs' structural development. This quest is done with other partners such as Advanced Manufacturing Technology providers, universities, sectoral technology centres, associations, competitors, and customers. Through this multidisciplinary collaboration, it is possible to deepen knowledge of the economic potential of OS resources and improve productive investment and market access (RQ2).

Through consortia formed to mobilise R&D projects, stimulated cross-company and cross-institutional collaboration is key to improving agility, productivity gains and increasing the ability to respond to market demand while reducing raw material waste, energy consumption and environmental impact (RQ3). Nevertheless, as mentioned above, not all Portuguese OS companies have adopted Leanstone technologies. They still work traditionally, i.e. they do

not have digital production machines in the factory halls and communicate with the market only by phone and email.

Regarding the expected contribution, this study highlights the synergy and collaboration between OS Cluster and stakeholders (government and policies, high-tech companies, research centres and universities) in RDMPs and I4.0 implementation. Based on the OS cluster practices and RDMP findings, the framework developed for this study will be a valuable resource for organisations implementing I4.0 technologies and conducting R&D. This framework will help to understand how innovation in the RDMPs represents a breakthrough in the OS industry. This review justifies a business policy for the Portuguese OS sector supported by a collaborative operational network under I4.0 technology. Innovative practices, new technologies, and lean thinking methodologies introduced by RDMPs are discussed as business interests and impacts.

Although the proposed objectives were broadly achieved, this study has some limitations. As this is a conceptual work, the main limitation is that the concepts discussed must be scientifically validated. Future research will focus on addressing this limitation. The second limitation concerns the small number of studies, as the research topic is new. Few studies address the impact of I4.0 and technical innovations from RDMPs on the performance and sustainability of OS companies. In the context of this research problem, possible future developments could include a dynamic analysis of the cost-benefit ratio and an interpretation of the boundary conditions. This inclusion would relate to the investment required to join RDMPs and a life cycle assessment of OS-manufactured products in a BIM context. In conclusion, some questions arise from our review: (i) How should one invest in digitalisation? (ii) How much should you invest? (iii) What is the return on investment? (iv) What are the direct returns on investment? Moreover, (v) What are the indirect gains from the investment?

We hope to address these questions in our future work.

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