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Innovation and Sustainability in the Portuguese Ornamental Stone Industry: Leveraging Industry 4.0 Technologies within the SCOR Model

Luís Miguel Fonseca da Costa

Master's (MSc) in Management of Services and Technology

Supervisors:
PhD, Isabel Cristina de Seixas Patrício Duarte de Almeida,
Invited Assistant Professor,
Iscte-IUL

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BUSINESS
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Dedicated to my parents, São and Hermínio

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Acknowledgements

When I left my job and returned to student life to pursue a Master's at Iscte Business School, I knew there would be hard work ahead, but I can now also say that the gratification I gained throughout this process made every challenge worthwhile. With that in mind, my first acknowledgment goes to all the professors that I had the opportunity to work with during the Masters. Thank you for the lessons and insights that expanded my horizons and deepened my knowledge. I have no doubts or regrets about the decision I made, or the Master's program I have chosen.

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To my friends at Frontwave, for all your guidance and for helping me connect with stakeholders from the OS industry.

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Resumo

Esta pesquisa aborda a necessidade de aumentar a inovação e as práticas de sustentabilidade na indústria portuguesa de pedra ornamental, alavancando as tecnologias da Indústria 4.0 (I4.0) e integrando-as no Modelo SCOR. O estudo visa encontrar soluções para os desafios enfrentados por esta indústria na adoção de tecnologias avançadas para melhorar a eficiência operacional e reduzir o impacto ambiental, mantendo a sua competitividade no mercado global.

A investigação analisa a interligação entre inovação e sustentabilidade, os desafios específicos da indústria, a integração de tecnologias I4.0, os objetivos de sustentabilidade mais amplos e a relevância do Modelo SCOR para melhorar a eficiência e a sustentabilidade das operações da cadeia de suprimentos.

Através de entrevistas com líderes do setor, a pesquisa irá procurar identificar os fatores críticos de sucesso e as melhores práticas para incorporar inovação, sustentabilidade e tecnologias I4.0, com o objetivo final de criar um guia para as partes interessadas da indústria sobre como alavancar efetivamente estas as tecnologias, tendo o Modelo SCOR como estrutura e métrica para melhorar as operações da cadeia de abastecimento, a competitividade e a sustentabilidade do setor.

Palavras-chave: Indústria 4.0, sustentabilidade, rochas ornamentais, Modelo SCOR, inovação, cadeia de abastecimento

Classificação JEL: Q01 (Desenvolvimento Sustentável), Q56 (Sustentabilidade), Q3 (Recursos não-renováveis e Conservação)

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Abstract

This research addresses the need to enhance innovation and sustainability practices within the Portuguese ornamental stone industry by leveraging Industry 4.0 (I4.0) technologies and integrating them into the SCOR Model. The study aims to find solutions to the challenges faced by this industry in adopting advanced technologies to improve operational efficiency and reduce environmental impact, while maintaining its competitiveness in the global market.

The research analyzes the interrelation between innovation and sustainability, the industry's specific challenges, the integration of I4.0 technologies, broader sustainability goals, and the relevance of the SCOR Model for improving the efficiency and sustainability of supply chain operations.

Through qualitative interviews with industry leaders, the research will seek to identify critical success factors and best practices for incorporating innovation, sustainability, and I4.0 technologies, with the ultimate goal of creating a guide for industry stakeholders on how to effectively leverage these technologies, using the SCOR Model as a framework and metric to enhance supply chain operations, competitiveness, and sustainability within the sector.

Keywords: Industry 4.0, sustainability, ornamental stone, SCOR Model, innovation, supply chain

JEL Classification: Q01 (Sustainable Development), Q56 (Sustainability), Q3 (Nonrenewable Resources and Conservation)

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List of Abbreviations

AGV – Automated Guided Vehicle

AI – Artificial Technology

AM – Additive Manufacturing

AR – Augmented Reality

ASSIMAGRA – Portuguese Association of Mineral Resources Industry

BDA – Big Data & Analytics

BI - Business Intelligence

CDO – Chief Digital Officer

CNC - Computer Numerical Control

CPS – Cyber-Physical Systems

DT – Digital Twins

ERP – Enterprise resource planning

EU – European Union

I4.0 – Industry 4.0

IIoT – Industrial Internet of Things

IoS – Internet of Services

IoT – Internet of Things

IT – Information Technologies

KPI – Key Performance Indicator

MIR – Mobile Industrial Robots

ML – Machine Learning

OS – Ornamental Stone

OSCM – Operational Supply Chain Management

QDAS – qualitative data analysis software

QR – Quick Response

R&D – Research and Development

RFID – Radio-Frequency Identification

SCOR – Supply Chain Operations Reference

SDG – Sustainable Development Goal

SDG – Sustainable Development Goals

SME – Small and Medium enterprises

S-OSCM – Sustainability in Operations and Supply Chain Management

UN – United Nations

VR – Virtual Reality

WCED – World Commission on Environment and Development

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CHAPTER 1. INTRODUCTION

The introduction seeks to provide a context for the conducted research, elucidating the reasons behind the dissertation, outlining both the overarching and specific goals and posing the associated research questions. Additionally, it will outline the planned methodology and conclude with a concise overview of the document's structure.

1.1 Contextualization

The Portuguese ornamental stone (OS) industry is a sector that produces and export types of natural stones, such as granites, marbles, limestones, and others. Being one of the oldest in the stone industry, it represents a high-value-added sector. This industry yields a wide array of products, predominantly for the construction sector, encompassing wall and floor coverings, as well as large-scale blocks for diverse applications. The main types of rocks extracted as ornamental stones are marble, limestone and granite, and the OS quarry distribution in Portugal is represented in the map of Figure 1.1:

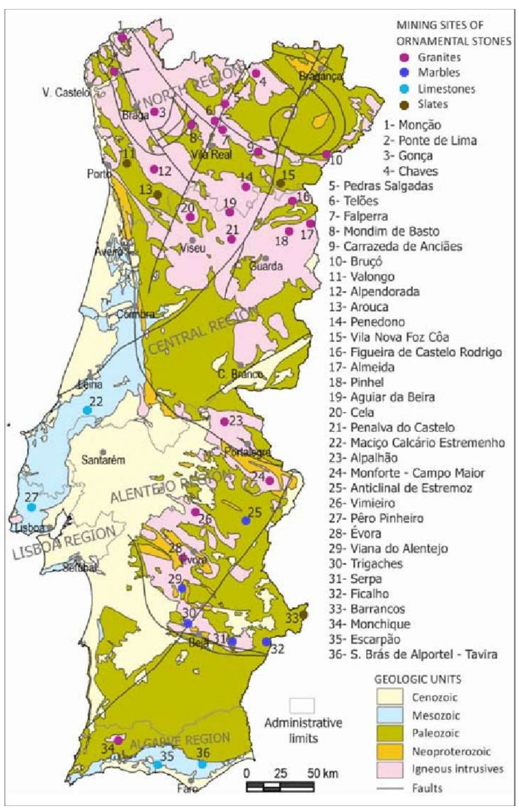

Figure 1.1 Portuguese Geologic Units (Carvalho et. al., 2013)

It has had an average annual growth of 4% since 1970 (Carvalho et al., 2018), representing more than 430 million euros in exports in 2021 (ASSIMAGRA, 2022), which is where its products are primarily destined to be.

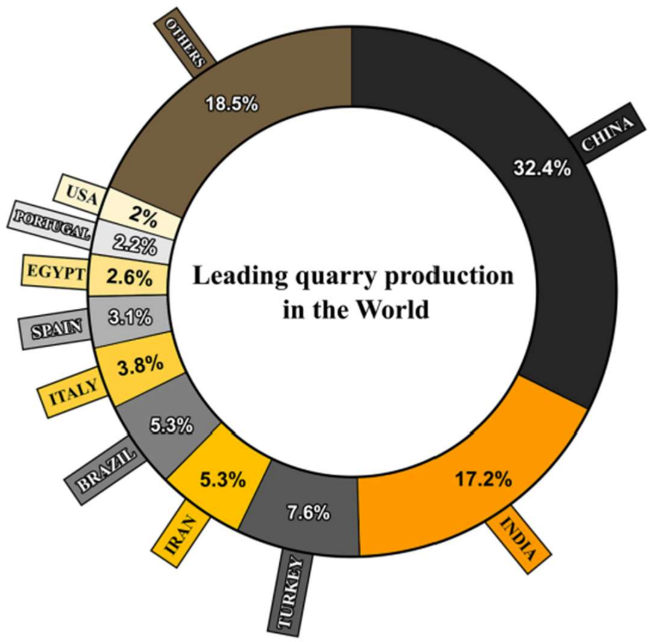

Figure 1.2 Leading countries in dimension stone production in 2020 (Montani 2020)

The sector encompasses two distinct economic activities: extraction and processing. Extraction refers to the quarrying or mining of raw stone blocks, employing methods like diamond wire cutting and explosives based on the stone type and quarry characteristics. Processing then transforms these raw blocks into usable forms, such as slabs or tiles, through cutting, shaping, polishing, and applying various surface treatments.

As a nonrenewable industry, it involves increased resource consumption and waste production, as well as an impact on countries' landscapes.

The Portuguese OS Industry faces problems similar to those of other industries, including rising energy and transport costs and labor shortages, such as difficulties in hiring or retaining human resources (Silva R., 2022). Adopting new strategies and technologies might help unlock new productivity levels and surpass these difficulties.

1.2 Problem Statement

This research addresses the need to enhance innovation and sustainability practices within the Portuguese OS industry by leveraging Industry 4.0 (I4.0) technologies and integrating them into the SCOR (Supply Chain Operations Reference) Model. The study seeks to find solutions to the challenges faced by this industry in adopting advanced technologies to improve operational efficiency and reduce environmental impact while maintaining its competitive edge in the global market.

The following five insights will be addressed in the literature review to understand the context of the problem. These insights follow the key concepts of Bloom’s Taxonomy, namely, knowing, understanding, applying, and analyzing:

- Provide an overview of how innovation and sustainability are interlinked and the importance of the former in the latter.
- Identify the industry's specific challenges, such as competitiveness, resource efficiency, environmental concerns, or technological gaps.
- Explore the integration of I4.0 technologies such as automation, Internet of Things (IoT), data analytics and digitalization into the ornamental stone sector to uncover opportunities for improved efficiency, sustainability, and technological innovation.
- Consider and analyze the broader sustainability goals in the OS industry, including the United Nations (UN) Sustainable Development Goals (SDG), environmental regulations, customer demands for sustainable products, and social responsibility.
- Describe and explain the SCOR Model and demonstrate its relevance to the OS industry, including its potential to improve efficiency and sustainability of supply chain operations.

1.3 Research Objective

As stated by Caiado et al. (2022), there is a notable gap regarding integrating I4.0 and sustainability in Operational Supply Chain Management (OSCM). Existing frameworks in the literature typically address Sustainable Supply Chain Management challenges and propose corresponding solution measures, contributing to the advancement of sustainability practices in traditional supply chains. However, none of these frameworks effectively establish the crucial links between the challenges associated with integrating I4.0 technologies and sustainability in OSCM. Also, Cañas et. al 2020 noted a need to create a framework that can combine sustainability and I4.0.

The problem of enhancing innovation and sustainability in the Portuguese ornamental stone industry by leveraging I4.0 technologies within the SCOR Model is interesting from both practical and scientific perspectives.

The OS industry is economically important in Portugal, contributing significantly to exports and employment, but it significantly impacts the environment. Improving its competitiveness and sustainability will have a positive impact on the country's economy. Hence, finding ways to make this industry more sustainable is crucial, especially in the context of increasing environmental awareness and regulations **(Goal 1).**

In the free and global market of ornamental stones, it is wise to enhance global competitiveness for Portuguese ornamental stone companies through the strategic integration of I4.0 technologies and efficient supply chain models **(Goal 2).**

This could be achieved by studying the practical challenges of adopting advanced technologies in a traditional industry.

The research will address the challenges arising during transitions, focusing on identifying solutions. The results will be analyzed with a view to broader application and provide insights applicable to industries of the sector undergoing similar transformations **(Goal 3).**

The research will consist of four stages, starting with the literature review based on bibliographic research. After that, there will be a theoretical approach, transferring theoretical ideas to the field of observation and considering the research questions. Phase three involves conducting the research, gathering the data from the interviews, processing the resulting data, and culminating with a qualitative analysis of the interview data as the final stage.

This research is expected to address challenges such as competitiveness, resource efficiency, environmental concerns, and technological gaps. It will utilize in-depth interviews with industry leaders to uncover insights into the integration of relevant I4.0 technologies. Expected results include a comprehensive understanding of how these technologies can improve operational efficiency and foster sustainability within the Portuguese OS industry.

Furthermore, the research aims to identify key success factors and best practices for integrating innovation, sustainability, and I4.0 technologies while using the SCOR Model framework. The study seeks to provide valuable insights applicable to other sectors undergoing similar transitions by exploring practical challenges associated with adopting advanced technologies in a traditional industry. Ultimately, it is wanted to create a guide for industry stakeholders on effectively leveraging I4.0 technologies, enhancing supply chain operations, competitiveness, and sustainability for the sector.

1.4 Research Questions

To achieve the proposed research objectives in the dissertation, the following questions arise:

RQ1: What I4.0 technologies are relevant to the ornamental stone industry?

RQ2: What are the key success factors and best practices for integrating innovation, sustainability, and I4.0 technologies in the OS industry?

RQ3: How can I4.0 technologies be effectively integrated into the OS industry's value chain, and how can success be measured?

1.5 Research Methodology

This research will use a qualitative approach, interviewing key industry participants. These interviews will involve open-ended, in-depth conversations with individuals to gather rich and detailed information about their experiences, perspectives, and insights. Unlike quantitative methods that focus on numerical data and statistical analysis, qualitative interviews aim to explore the complexity and depth of a phenomenon (Saunders et al., 2009).

Conducting interviews with key industry stakeholders is expected to uncover insights into the challenges and opportunities and reveal their depth of knowledge about the subjects. Unlike a deductive approach, which might be too rigid in defining variables, an inductive methodology acknowledges contextual nuances, providing flexibility to identify alternative explanations and new insights (Saunders et al., 2009).

After the interviews, the responses will be prepared for analysis by transcribing and then summarized, categorized, and structured so they can be studied and interpreted.

1.6 Scope

Delimitations are essential to specify the boundaries and constraints of the study. In the context of this research, the delimitations included are:

- The research focuses on specific subsectors of the ornamental stone industry rather than addressing the stone and mining industry as a whole.
- The study is geographically focused on the Portuguese ornamental stone industry, meaning the findings and solutions may not be directly transferable to other industries, sectors, or regions.

1.7 Structure of the thesis

Based on the objectives intended to be achieved, this dissertation in Management of Services and Technology is structured into five chapters. Initially, an introduction is provided, encompassing the contextualization of the research project, the identification and explanation of the main objective, the methodology employed, and an overview of the document's structure.

A literature review will be conducted in the second chapter to deepen the theoretical knowledge supporting the entire project.

Subsequently, the adopted methodology will be presented in the third chapter, playing a crucial role as a guiding framework for the entire research. In this highly significant section, the objective is to identify all data collection methods and tools, which will be essential to achieving the goals established in the first chapter.

In the fourth chapter, the interviews conducted will be presented and analyzed, and their results will be discussed considering previous literature review.

Lastly, in the fifth chapter, it is presented and lay down the final conclusions of this dissertation, as well as its limitations and suggestions for future investigation.

CHAPTER 2. LITERATURE REVIEW

This Literature Review establishes the theoretical framework for concepts closely related to and supporting the research topic. It also surveys existing empirical studies in the field, aiming to address this dissertation's objectives and research questions.

The focus is initially on examining the concepts of innovation and sustainability. Subsequently, an exploration of the current environmental policies and regulations in place or being implemented in Portugal and Europe is undertaken. The research then delves into the understanding of I4.0 and the SCOR Model, followed by an exploration of how these concepts can be integrated.

The literature review was conducted using search engines such as B-On and Science Direct. Keywords such as “innovation,” “sustainability,” “Industry 4.0,” “Supply Chain 4.0,” and “Ornamental Stone” were employed in this research.

2.1 Innovation

“Innovation is probably the single biggest factor determining who succeeds and who fails anywhere in the world.” – Nick Donofrio, IBM Corporation, Global Innovation Outlook, 2007.

Innovation is creating something new, be it a product, process, technique, system, or business model. It can also involve modifications or adaptations to existing elements to make them more sustainable or efficient (Dey et al., 2019). The core purpose of innovation is to create economic, social, or environmental values. It’s not just about creating something new but ensuring it positively impacts stakeholders and the world (Gupta et al., 2020).

Innovation is often driven by the need to address challenges or pressures such as sustainability, climate change, resource depletion, competition, or customer demands. It's a continuous process of experimentation, learning, and adaptation. Organizations that want to remain competitive must integrate innovation into their operations and culture (Kusi-Sarpong et al., 2018).

Innovation can manifest in various forms, including product innovation (developing new products or improving existing ones), process innovation (implementing new or improved production or delivery processes), organizational innovation (introducing new organizational practices, structures, or business models), sustainable innovation (creating products, processes, or business models that reduce environmental impact, promote social equity, or are economically viable), and eco-innovation (innovation specifically aimed at reducing the environmental impact of products or processes) (Dey et al., 2019)..

Several factors can influence innovation, such as strong leadership commitment is essential, with company management supporting and directing innovation initiatives. This includes allocating resources, setting clear goals, rewarding risk-taking and experimentation and maybe even the creation of a Chief Digital Officer (CDO) (Birkel et al., 2019). Companies encouraging experimentation and viewing failure as a learning opportunity are more likely to innovate successfully. Effective communication across departments, especially between Information Technologies (IT) and other areas, is also crucial to avoid information silos and promote collaboration. Rigid hierarchies can also stifle innovation, so companies must adopt more agile and adaptable structures that can respond quickly to market changes and new opportunities. For example, this can be done by creating multidisciplinary teams and decentralizing decision-making, which can further increase creativity and accelerate innovation (Hargadon, 2015). A strong leadership commitment with a clear view is important for successful implementation of innovation, to avoid creating confusion within its organization, especially as there are no unique solution to overcome the barriers to innovation (Gupta et al., 2020).

A company’s ability to innovate can also be influenced by external factors such as competitive pressure and this can be a powerful driver forcing companies to constantly seek ways to differentiate themselves and offer more value to customers (Hargadon, 2015; Birkel et al., 2019). Collaboration between companies, technological companies, start-ups and academia can create alliances to overcome the barriers and difficulties that innovation such a I4.0 impose to them, promoting innovation, knowledge sharing and reducing costs. And this is also true in terms of funding. As majority of businesses are small-medium enterprises (SME), that usually they do not have the capital need to fund their investment in Research and Development (R&D). Several State and European Union (EU) programs exist that help companies build new business models while reducing the risk that such investments cause. (Machado et al., 2021; Birkel & Müller, 2020).

2.2 Industry 4.0 and related technologies

I4.0 was a term coined by the German government in 2011 to mobilize the country's manufacturing industry to a fast-paced technological new world (Birkel & Müller, 2020). Industries are facing increasing requirements regarding cost efficiency, flexibility, adaptability, stability, and sustainability. The traditional approaches to value creation may not be sufficient to meet these requirements anymore. However, new businesses' potentials and opportunities have emerged due to rapid technological progress in recent years. Digitalization, the IoT, the Internet of Services (IoS), Big Data, Artificial Technology (AI), and cyber-physical systems (CPS) are some of the new trends that are becoming more and more relevant (Hofmann & Rüsch, 2017), (Javaid, Haleem, Singh, Suman, & Gonzalez, 2022).

It is factual, as stated by M. Mabkhot et al. (2021), that a range of different technologies proceeded with the idea of I4.0 for several decades, however they are being applied in a way that is more sensible and collaborative than ever before, transforming the existing business landscape.

Figure 2.1 resumes I4.0 technologies and their enablers:

Figure 2.1 I4.0 enablers and elements technologies (M. Mabkhot, et al., 2021)

Some technologies and enablers of I4.0 include:

- Digitalization: This is the integration and optimization of information and the flow of goods throughout the supply chain and involves converting physically collected information (for example, by sensors or written records) into a computer-readable language. It is an enabler and a fundamental requirement for achieving I4.0, driving real-time interconnection within and between companies and supply networks (Caiado, et al., 2021; Birkel & Müller, 2020).
- Internet of Things (IoT) / Industrial Internet of Things (IIoT): Considered one of the pillars and an initiator of I4.0, IoT autonomously connects devices, machines, products, and systems in an intelligent network along the value chain. The IIoT is the application of IoT in the context of the I4.0 to leverage and realize its functionalities and key elements of the IIoT include general identification, ubiquitous sensing, and continuous, high-speed communication (Hofmann & Rüsch, 2017; M. Mabkhot, et al., 2021).
- Big Data & Analytics (BDA): This refers to large, heterogeneous datasets from various sources, with different formats, that flow in real-time. BDA involves the use of advanced AI data analysis techniques, including machine learning (ML) and deep learning algorithms, to extract valuable knowledge from large volumes of data and support data-driven decision-making. BDA is one of the most studied technologies in the context of Industry 4.0 and sustainability in operations and supply chain management (S-OSCM) (M. Mabkhot, et al., 2021).
- Artificial Intelligence (AI) and Machine Learning (ML): AI is a main component of I4.0, enabling machines to autonomous decision-making. ML and deep learning algorithms are an integral part of Big Data analysis. These technologies help manage large volumes of data and optimize processes and equipment, reducing human error and increasing production consistency (Javaid et al., 2022).
- Cyber-Physical Systems (CPS): These constitute the technological core of Industry 4.0. CPS merge the real and virtual worlds, allowing for real-time data transfer between people and objects along the entire value chain. Each physical device in a CPS has a cyber part as a digital representation, culminating in "digital twin" models (Birkel et al., 2019).
- Additive Manufacturing (AM) / 3D Printing: Allows for the creation of customized parts and can reduce supply risks by enabling the replacement of missing materials.
- Cloud Computing: Offers IT infrastructure resources as a service over the internet, covering the entire product lifecycle.

- Augmented Reality (AR) / Virtual Reality (VR): AR enhances human perception by overlaying computer-generated information onto the real-world environment and is used for training and simulation.
- Autonomous Robots / Advanced Robotics: Intelligent machines capable of performing tasks without explicit human control, such as Automated Guided Vehicle (AGV) or Mobile Industrial Robots (MIR).
- Digital Twins (DT): Virtual models of physical properties, processes, systems, and equipment that allow for dynamic modeling, real-time simulation, and intelligent decision-making.

2.3 Sustainability

Sustainability has emerged as a global imperative, urging industries to re-evaluate their practices to minimize their adverse impact on the planet. However, the definition of sustainability remains somewhat fluid, lacking specificity and precision. Despite this ambiguity, a fundamental aspect of sustainability lies in the need to plan and execute resource exploration in a more sustainable way, ensuring the longevity of our planet for future generations (Careddu, 2019).

The Brundtland Report (1987) from World Commission on Environment and Development (WCED) was a landmark document that introduced the term "sustainable development" into the global lexicon, raising public awareness of the environmental impact of industrial manufacturing. It emphasized that a singular focus on profit maximization, without considering the broader concerns of stakeholders, is becoming increasingly unacceptable (Strandhagen et al, 2020).

Sustainability is a multifaceted concept that focuses on developing and implementing new products or processes that minimize socio-environmental impact, while ensuring financial viability for both manufacturers and consumers. This concept is often referred to as the triple bottom line, encompassing economic, social, and environmental dimensions (Brozzi et al., 2020).

- Economic sustainability: it implies long-term profitability and financial viability for businesses.
- Social sustainability: it focuses on the well-being of individuals and communities, including issues such as health, safety, and social equity.

- Environmental sustainability: it focuses on preserving natural resources, minimizing the environmental impact of industrial activities, and promoting practices such as recycling, waste management, and energy efficiency.

Integrating sustainability into business operations requires careful consideration of its multilayered nature. It must balance economic performance, ensuring long-term financial viability and value creation for stakeholders, with environmental impact, by minimizing greenhouse gas emissions, resource consumption, and waste. Additionally, it must prioritize social responsibility, encompassing ethical labor practices, community engagement, and respect for human rights throughout the supply chain (Franciosi et al., 2018).

OS industry uses a non-renewable resource, and 26% of it goes to waste when processed (Gadioli et al., 2022). Green innovation and I4.0 are important to maximize its use and, by increasing the efficiency of extraction and processing of the sector, it will help the sector to be more sustainable.

2.4 Environmental Policies and Regulations

The European Green Deal is a comprehensive and ambitious initiative launched by the European Commission, in December 2019. It serves as the EU's roadmap for transforming its economy into a sustainable and climate-neutral system with the ultimate goal of making the EU climate-neutral by 2050 (European Commision, 2023).

Mining and quarrying constitute a sector that produces approximately 27% and 37% of the total waste generated by all activities categorized in the European Community's statistical classification of economic activities (NACE) and households, respectively, based on Eurostat data from 2018 (Kulczycka & Dziobek, 2021). About 51% of material extracted from dimension stone quarries turns into waste during extraction, and approximately 41% of material entering dimension stone processing plants becomes waste during processing, resulting in an overall recovery rate of about 29%, which shows the considerable resource losses and substantial waste generation caused by this sector. (Jalalian et al., 2021). These numbers highlight the importance of discovering new tools and technologies that can support the industry with the growing number of regulations, especially as it is one with such a significant environmental impact.

According to some authors (M. Mabkhot, et al., 2021), I4.0 tools significantly impact the achievement of the United Nations' Sustainable Development Goals (SDGs). These technologies have a more prominent impact on SDG9 (Industry, Innovation, and Infrastructure), but there are variations across technologies and specific SDGs.

2.5 SCOR Model

The SCOR (Supply Chain Operations Reference) framework is a widely recognized and standardized model that describes, measures, and manages supply chain operations that is in its twelve version. It was developed by the Supply Chain Council (now part of the Association for Supply Chain Management, ASCM) and is designed to provide a common language and set of metrics for supply chain management. The primary goal of the SCOR framework is to help organizations analyze and improve their supply chain processes by providing a structured and standardized approach (APICS, 2017).

The SCOR model consists of six major process categories which are Plan, Source, Make, Deliver, Return and Enable. They are defined as following:

- **Plan**: Develop a strategy to balance supply and demand, align resources, and manage risks.
- **Source**: Procure goods and services, including selecting suppliers, negotiating contracts, and managing relationships.
- **Make**: Transform raw materials into finished products through manufacturing and assembly processes.
- **Deliver**: Fulfill customer orders by managing inventory, transportation, and order fulfilment processes.
- **Return**: Handle returned or defective products, including reverse logistics and disposal.
- **Enable**: This cross-functional process encompasses the management activities that support the other processes, such as workforce training, technology infrastructure, and performance measurement.

These processes cover the entire supply chain, from planning and sourcing raw materials to manufacturing, delivering products to customers, and handling product returns.

The SCOR model also incorporates performance metrics and best practices to help organizations assess and benchmark their supply chain performance. By using a standardized framework, companies can identify areas for improvement, streamline processes, and achieve greater efficiency and effectiveness in their supply chain operations (APICS, 2017).

In figure 2.2 it is shown the four levels followed in the SCOR Process Hierarchy.

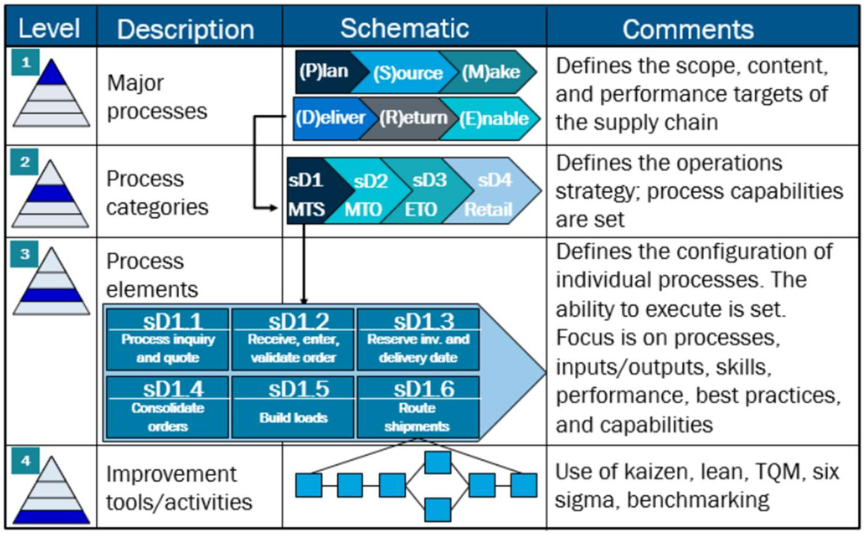

Figure 2.2 SCOR Process Hierarchy (APICS, 2017)

The SCOR model allows for a general vision of the different activities and processes of the value chain, regardless of the industry or sector. It provides a common language that all stakeholders can follow, making communication clearer. It provides benchmarks and best practices that are comparable between organizations, allowing them to identify opportunities to improve. And SCOR Model can be integrated on Enterprise resource planning (ERP) Systems or Big Data or other supply chain management platforms.

As Ayyildiz and Taskin Gumus (2020) suggest, the SCOR model can be expanded by incorporating additional metrics linked to I4.0 and digitalization. This expansion aims to comprehensively assess and comprehend supply chain performance, proposing an innovative SCOR 4.0 model organized with a three-level hierarchical structure for evaluating the entire supply chain.

Equally, incorporating I4.0 and circular economy practices in manufacturing organizations is imperative for global competitiveness. Therefore, adopting solution measures grounded in I4.0 and circular economy principles will enable organizations to use advanced technologies and integrate sustainability into their current supply chain (Yadav et al., 2020).

2.6 Literature Review Summary

The ornamental stone industry, traditionally associated with the extraction and processing of natural resources, faces the pressing challenge of aligning its operations with the principles of sustainability. In this context, innovation driven by I4.0 emerges as a crucial catalyst for the sustainable transformation of the sector.

I4.0, characterized by the integration of digital technologies such as the Internet of Things (IoT), cloud computing, and big data analysis, offers a wide range of tools and opportunities to optimize processes, reduce waste, and promote environmental sustainability. The digital interconnection provided by I4.0 allows for real-time monitoring of energy and resource consumption, identification of inefficiencies, and implementation of corrective measures, contributing to the reduction of the environmental footprint of the ornamental stone industry (Birkel et al., 2019).

Furthermore, innovation fueled by I4.0 enables the incorporation of waste from ornamental stone production into new materials, promoting a circular economy and both economic and environmental sustainability (DilliBabu, et al., 2023). For example, the use of diamond wire cutting technologies for granite minimizes waste production compared to traditional methods.

I4.0 also fosters the creation of cooperative networks between companies in the ornamental stone sector, driving collaborative innovation and value creation. Sharing resources, knowledge, and technologies through digital platforms, such as Cockpit4.0, enables companies to develop innovative products and services, differentiate themselves in the market, and reach new customers.

The convergence of innovation, sustainability, and I4.0 in the ornamental stone industry aligns with the SDGs, particularly SDG 9 and SDG 12 (da Silva & Almeida, 2020). By integrating digital technologies, optimizing processes, and promoting a circular economy, the ornamental stone industry can contribute to building a more sustainable future that is both economically viable and socially responsible.

The transition to a more sustainable ornamental stone industry, driven by innovation and I4.0, faces significant challenges, and a framework such as the SCOR Model may support in surpassing them in a systematic and methodic way.

Portuguese OS industry has actively worked in reducing waste and improving flexibility since 2004 as detailed by (Frazão, 2018). Developed by collaborative associations of companies and public organizations like universities, these initiatives include projects such as Jetstone (2005), Inovstone (2010), and Inovstone 4.0 (2017) or Inovmineral (2023). The sector is adapting to the new industrial paradigm focused on digitalization and building common foundations on these projects to optimize resource use, reduce waste, and enhance efficiency, aligning with sustainability goals (Frazão, 2018). Innovation drives the Portuguese OS industry by adopting I4.0 technologies, such as IoT sensors, big data, and automation, which help companies stay competitive and meet the demand for eco-friendly products.

On the other hand, the SCOR model integrates these concepts into the supply chain, covering Plan, Source, Make, Deliver, Return, and Enable. Also, Data analytics optimize planning and inventory, while automation improves precision and reduces costs. Sustainability metrics in each stage ensure progress towards environmental goals, positioning the industry for future growth and long-term viability.

CHAPTER 3. METHODOLOGY

This chapter presents the research methodology applied to address the research questions.

3.1 Research Context

Portugal holds a significant position in the global natural stone market, ranking as the seventh largest producer and extractor. In the most recent reporting year, the country exported 488 million euros worth of ornamental stone, with France, China, and Spain being the primary destinations. The sector accounts for 0.6% of Portugal's total exports. (Castro, 2024).

According to Portuguese Association of Mineral Resources Industry (ASSIMAGRA), the OS industry generated 1.2 billion euros in revenue in 2023. Data from 2022 indicates the industry consisted of 2,066 companies (approximately 80% focused on processing and 20% on extraction) and provided employment for 14,052 individuals (with roughly 70% in processing and 30% in extraction roles) (Castro, 2024). Despite a minor decrease compared to the previous year, the figure 5.1 shows the evolution of the total exports from the sector since 2010, with a total increase of around 60%, as shown in the figure:

Figure 3.1 Portuguese OS Exportation Value (Millions of €) (Source: ASSIMAGRA)

3.2 Research Design and Methodology Approach

This study utilizes a qualitative research approach to gain an in-depth understanding of the complex dynamics surrounding I4.0 adoption, sustainability initiatives, and innovation within the Portuguese OS industry.

A qualitative methodology was selected because it is particularly because, through it, one can thoroughly study complex subjects, understand firsthand experiences, and uncover the very core motivations, influences, and challenges identified by key stakeholders across the industry. As opposed to quantitative approaches, which emphasize numbers and statistical analysis in order to confirm existing theory or create generalizable knowledge, qualitative research seeks to gain an understanding of concepts, ideas, or experiences in great depth. This positions it especially well for subjects that are intricate or not yet clearly understood, with the possibility of revealing obscured causes and examining ideas to formulate emergent hypotheses or theories from actual real-world situations (Mexon & Kumar, 2020). This method supports an in-depth and contextual examination of the explanations and processes for which phenomena materialize within the specific context of the Portuguese OS sector, those aspects that cannot be captured using quantitative methods.

The main data gathering method employed was long, semi-structured, in-depth interviews with OS industry experts. This was chosen for its advantage of eliciting rich data, facilitating probing questions, and capturing the opinions of those personally involved in making decisions related to I4.0, sustainability, and innovation. This directly translates to the research objective of understanding the actual challenges, opportunities, and drivers in their companies.

The research started with a comprehensive literature review to establish a robust theoretical foundation and inform the development of the interview guide. This was followed by the OS industry expert interviews. The findings from both the literature and the interviews were subsequently analyzed and synthesized to provide an in-depth understanding of the research topic, specifically addressing the research questions and objectives.

3.3 Data Collection

The research population targeted in this research was managers, directors, and executives from Portuguese OS firms operating in extraction or processing activities. The initial list of 40 possible respondents was compiled from business directories and industry association contacts with a view to having a satisfactory range in terms of firm size, geographical coverage within Portugal, and primary function (extraction, processing, or both).

These participants were contacted with interview requests. Of the foregoing requests, twelve participants from various companies consented to participate in the study. Although this group constitutes a purposive sample by willingness and availability to participate, the resulting cohort (as established in Table 3.1) does comprise a varied combination of organizational size, leadership role, geographic location, and functional focus in the industry and, as such, imbues the qualitative data with useful diversity.

An interview script was developed based on the research questions and key themes identified in the literature review. It was designed to explore concepts related to I4.0 awareness and implementation, sustainability practices, drivers and barriers to innovation, perceived impacts, and challenges specific to the Portuguese context. The interview guide consisted of thirteen main questions, organized into four categories:

1. Industry 4.0 general knowledge
2. Company context with Industry 4.0
3. Challenges and External Factors
4. Portuguese Ornamental Stone Industry and I4.0 Impacts

Prior to the main data collection phase, a pilot interview was conducted with an industry professional (not included in the final sample) to test the clarity, relevance, and flow of the questions, and to estimate the required interview time. Minor adjustments were made to the wording of some questions based on feedback from this pilot test to enhance comprehension and ensure the instrument effectively captured the necessary information.

- **Interview Procedure:** All twelve interviews were conducted between May and July 2024 via online meeting platforms. With explicit consent from each participant, the interviews were audio-recorded to ensure accurate transcription. Each interview lasted approximately 45-60 minutes.

- **Participant Profile Summary:** The table below (Table 3.1) summarizes the profile of the participating companies and the job roles of the interviewees. Company names have been anonymized to ensure confidentiality.

Table 3.1: List of Companies Interviewed

Company	Position	# Employees	Region	Sector
#1	Chairwoman	59	Porto de Mós	Extraction & Processing
#2	CFO	80	Santarém	Extraction & Processing
#3	CEO	38	Alcobaça	Extraction & Processing
#4	Director	80	Vila Viçosa	Extraction & Processing
#5	Director	100	Viseu	Processing
#6	Director	90	Fátima	Extraction & Processing
#7	Manager	90	Santarém	Extraction & Processing
#8	CEO	46	Rio de Maior	Processing
#9	COO	98	Serra d'Aire	Extraction & Processing
#10	Manager	60	Pêro Pinheiro	Extraction & Processing
#11	Manager	50	Penafiel	Extraction & Processing
#12	Manager	70	Viana do Castelo	Extraction & Processing

It was decided to stop the interview process after twelve interviews as this is often sufficient for qualitative research aiming to understand common experiences within a relatively homogeneous group using semi-structured interviews. Data saturation largely occurred within the first twelve interviews and approximately 88% of all thematic codes were identified by the twelfth interview. Code definitions and thematic prevalence showed considerable stability by this point, with 97% of eventual high-frequency themes identified. (Guest et al., 2006).

3.4 Data Analysis

A thematic analysis approach was adopted to analyze the transcribed interview data systematically. This process involved several stages:

1. **Transcription and Familiarization:** All recorded interviews were transcribed. It was then thoroughly read to become deeply familiar with the content.

2. **Manual Coding:** Relevant segments of text related to the research questions and objectives (e.g., mentions of specific I4.0 technologies, sustainability concerns, innovation barriers, success factors, market perceptions) were identified and assigned descriptive codes.

3. **Theme Development:** Similar codes were grouped together to identify initial patterns and potential themes.
4. **Theme Review and Refinement:** These potential themes were reviewed, compared, merged, or split to develop a coherent set of core themes accurately reflecting the data.
5. **Analysis and Interpretation:** The finalized themes were analyzed across all interviews, identifying similarities, differences, and key insights. This comparative analysis formed the basis for addressing the research questions.

No specific qualitative data analysis software (QDAS) was used; coding and thematic development were performed manually.

3.5 Validation and Reliability

To enhance the trustworthiness and credibility of the findings, the following measures were taken:

- **Triangulation:** Findings derived from the interview data were compared with the existing academic and industry literature reviewed earlier in the study. This helped to corroborate or identify divergences between expert opinions and established knowledge.
- **Peer Debriefing:** Preliminary findings and interpretations were discussed regularly with research supervisors and peers. This process provided critical feedback, challenged assumptions, and helped refine the analysis, enhancing the reliability of the interpretations.

3.6 Ethical Considerations

All participants received detailed information about the study's purpose, procedures, potential use of data, and their rights before agreeing to participate. Written or verbal informed consent was obtained from each interviewee prior to the interview and participants were informed that the call was recorded and would be transcribed. Participants were informed that their involvement was entirely voluntary, and they could withdraw at any stage without penalty.

To protect participants and their organizations, anonymity and confidentiality were guaranteed. Company names were replaced with codes (e.g., Company #1), and any potentially identifying information within the transcripts was anonymized before analysis and reporting (as reflected in Table 3.1).

Interview recordings and transcripts were stored securely on password-protected devices, and used solely for the purposes of this study.

3.7 Limitations and Potential Biases

As a qualitative study with a sample size of 12 participants, the findings provide in-depth insights but may not be statistically generalizable to the entire Portuguese OS industry. The sample was purposive, relying on participant willingness, which could introduce selection bias.

Interviewees' responses might be influenced by social desirability or reflect their specific company's perspective or interests. Assurances of confidentiality were provided to mitigate this, but it remains a potential factor.

Although a semi-structured guide was used, the interviewer's interpretation or probing questions could potentially influence responses. Efforts were made to maintain neutrality and adhere closely to the guide.

Twelve interviews may prove insufficient if the chosen group exhibits significant heterogeneity, if the data quality is substandard, or if the research topic is broad or ill-defined. Furthermore, larger sample sizes are necessary when the research aim involves evaluating differences between distinct groups or examining correlations among variables. (Guest et al., 2006)

The study relies on the perceptions and reports of the interviewees, which reflect their individual understanding and experiences.

CHAPTER 4. RESEARCH RESULTS

4.1 Summary of Interviews

RQ1: What Industry 4.0 technologies are relevant to the ornamental stone industry?

The first part of the interview aimed to assess the interviewees' understanding of Industry 4.0 and the tools with which they were familiar.

All companies surveyed indicated that they have made some type of investment in technologies related to I4.0, although at different levels and with varying degrees of success.

Robotics and automation are central to the I4.0 vision for the stone sector. Many interviewees emphasize automation's importance for increasing efficiency, reducing labour dependence, and improving final product quality. Implementing robotics in production lines allows for complex tasks to be performed with greater precision and speed. Interviewee #5, for example, has been using robotics since 2009 and highlights its importance for staying competitive with China. However, implementing robotics also presents challenges, such as the need for investment in machines and software and the adaptation of production processes.

Another important aspect mentioned by most interviewees is digitalization, which is crucial for modernizing the sector, impacting processes from stock management and production control to order tracking. ERP software, for example, is essential for integrating different aspects of operations and enabling real-time monitoring. Using digital platforms for stock control, as interviewee #7 does, allows for more efficient management and better order tracking. Companies recognize that digitalization brings significant advantages in efficiency, cost reduction, and informed decision-making.

Computer Numerical Control (CNC) machines, already widely used in the sector, are essential tools for mass personalization stone products. With digitalization, these machines can be programmed to cut and shape stone with high precision, meeting the demand for customized products. 3D modelling and scanners are complementary technologies that enable the creation of detailed designs and optimize material use. Interviewee #6 highlights the importance of 3D in the sector's future, allowing for the creation of highly customized products. Interviewee #11, on the other hand, is skeptical about the technology's ability to adapt to the variability of natural stone.

Another I4.0 tool used, although not yet widespread in the sector, the IoT has the potential to revolutionize the ornamental stone industry. It allows for the collection of data from machines and would optimise production, reduce waste, and improve efficiency. Interviewee #7, for example, uses a digital platform to record machine maintenance and fuel consumption, but Interviewee #11 questions the usefulness of IoT in the quarrying industry, believing that the technology is not yet mature enough for this sector.

RQ2: What are the key success factors and best practices for integrating innovation, sustainability, Industry 4.0 technologies in the OS industry?

The successful implementation of I4.0 technologies in the ornamental rocks industry hinges on several critical factors. Firstly, a shift in mindset is crucial, companies need to adopt a long-term strategic vision that embraces the opportunities presented by I4.0, moving beyond immediate concerns and anticipating the future needs of the consumers. For many interviewees, the implementation of I4.0 tools was not supported by a strategic view. They saw it as a need to stay relevant in the market and because they knew their competitors were applying the tools. However, the ones that had were applying the tools together with a strategic view were being more successful in their implementation. Interviewee #1 said that strategy should align with their customers' priorities. Sustainability is a priority for them, and I4.0 tools are helping them achieve it. Their strategic perspective should prioritize investment in new technologies, software, and personnel training, recognizing the long-term return on investment. Such investments are essential to overcome the significant barrier presented by the lack of adequate management software, a common obstacle to I4.0 adoption.

A skilled workforce is vital, and the experience was different between companies. Companies recognize that they must prioritize the recruitment, training, and continuous upskilling of their employees to ensure they possess the necessary competencies to operate and manage new technologies. But like many industries, it was pointed out the difficulty in hiring and retaining employees, something that is being overcome by current migratory flows. Another major difficulty pointed out by majority of the interviewees was the difficulty in attracting talent and a new generation of skilled workers in digital tools. This focus on human resources is critical because the lack of qualified personnel is a major challenge to I4.0 implementation. Interviewee #10 pointed out that the older personnel were more resistant to the implementation of I4.0 tools and several different training courses were necessary to overcome them. And an insightful perspective is given by interviewee #9: after implementation of several digital tools and robots in their processing plant, it became more appealing to younger generations by transforming it into an activity akin “to playing Tetris”, where workers manipulate pieces on screens. OS industry workplace can be seen as dirty, loud and dangerous. With the use of innovative technologies, a safer and cleaner shopfloor can be built which can also attract a new generation of workers to the OS industry.

Effective collaboration is also key. Partnerships between companies, universities, and technology providers can drive innovation and the development of tailor-made solutions. By fostering the exchange of knowledge, expertise, and resources, collaboration accelerates the technology adoption process and promotes sustainability. All the interviewees mentioned that they have participated in the past or are currently working together in several R&D projects, in collaboration with companies from the sector, as well IT companies and public organizations.

To successfully implement I4.0, companies should adopt a range of best practices. Digitalization and automation are central, with the implementation of ERP, robotics, and automation to optimize processes, increase productivity, and reduce waste. These technologies enable more efficient resource control, improve product quality, and reduce operational costs.

Traceability and monitoring systems are essential to track products throughout the entire value chain, from extraction to final delivery, ensuring both quality and sustainability. This capability allows for better inventory management, supply chain optimization, and a more effective response to customer needs.

Sustainability should be a core principle, with the adoption of environmentally friendly practices such as reducing emissions, treating wastewater, and utilizing renewable energy sources. These efforts are crucial to minimize environmental impact and meet the growing demands of international markets, ensuring the industry's long-term competitiveness.

Continuous investment in training programs is vital to equip employees with the skills needed to operate new technologies and adapt to industry changes. This ongoing training ensures that the workforce is prepared for the challenges of I4.0, maximizing the return on technology investments and promoting innovation.

Data analysis and performance metrics (KPIs) should be utilized to monitor progress, identify areas for improvement, and make data-driven strategic decisions. This analytical approach enables more efficient resource management, process optimization, and the identification of innovation opportunities.

Finally, transparent communication across the organization, including with suppliers and customers, is crucial to facilitate collaboration, feedback, and adaptation to change. Open communication builds trust, aligns objectives, and enables effective problem-solving.

Despite the numerous benefits, several barriers can hamper the implementation of I4.0 in the ornamental rocks industry. All interviewees mentioned the high initial costs associated with technology and software investments, which can be a significant obstacle, especially as this industry is mainly composed of SME. Then there is the resistance to change, stemming from a lack of familiarity with new technologies and reluctance to abandon traditional methods, can also create internal challenges.

The lack of skilled professionals with the technical expertise and experience required to operate new technologies presents another hurdle.

The fragmented nature of the industry, comprised of many small-scale companies, can make it difficult to achieve large-scale technology adoption. As Interviewee #1 said, despite good collaboration between Academia and technological institutions, when it was between competing OS companies, it was difficult to work together.

RQ3: : How can Industry 4.0 technologies be effectively integrated into the OS industry's value chain, and how can success be measured?

The effective integration of I4.0 technologies into the OS industry value chain requires a strategic approach that involves all stages, from extraction, to processing and delivery.

One example mentioned by majority of companies interviewed was the ERP systems, and their impact on streamlining the business. Interviewee #4 was still in the early stages of implementing I4.0 tools in their production and business processes, and they were planning to add a new ERP. Currently, all their processes from giving a quotation to a customer, to transforming that quotation into work orders, to the create the outbound delivery and invoicing meant that a different Excel that needed to be processed individually. In contrast, Interviewee #5 had successfully implemented an ERP system to manage all value chain, streamlining each process into a linked one. It is possible to monitor each stage of the process, from the block in the quarry to the final piece in the client's building.

Again, digitalization plays a key role, allowing the creation of 3D models of blocks and pieces, facilitating production planning, optimizing cutting, and reducing material waste. The use of 3D scanners to digitize blocks and slabs allows for detailed analysis of their characteristics and optimized material selection, but also have them in clouds to show to customers worldwide.

The implementation of robotics and automation in key processes, such as cutting, polishing, and finishing, as well, as MIR or AGV for transportation, increases the efficiency and productivity of the OS industry. Interviewee #9 invested in automated production lines with robots which reduced the need for labor, increased production speed, and improve the accuracy and quality of products.

IoT sensors enable the collection and analysis of real-time data throughout the value chain. Machines can send reports on their performance, energy consumption, downtime, and production, which allows to identify inefficiencies, optimize processes, and make more informed decisions.

When asked about how were they measuring the success of integrating I4.0 technologies implementation in their businesses, and if there were specif metrics or KPI being measured and analyzed with frequency, all interviewees replied with a no. When asked if there were some ideas of metrics to be measured some suggested:

- productivity, such as the increased production per employee and per machine;
- efficiency: reduction in production cycle time, optimization of material use, and waste reduction;
- sustainability: reduction in energy and water consumption, reduction of carbon footprint, and increased reutilization of waste..
- Quality: Reduction of defects and customer complaints, increase in dimensional accuracy of parts.
- Profitability: Increase in profit margin per piece produced, reduction in production costs.

The interviewees also recognize the importance of standardized metrics for the sector, allowing comparison between companies and evaluation of the progress of the industry as a whole, which is something that lacks at the moment. This makes it difficult to benchmark the investments of each company in I4.0 and it’s impacts.

4.2 Discussion

4.2.1 I4.0 and Portuguese OS Industry

The Portuguese OS industry recognizes the importance of innovation and sustainability to remain competitive in the global market.

These are the main I4.0 technologies relevant to the Portuguese OS sector:

- Robotics: The use of robots in tasks such as cutting, polishing, and finishing increases efficiency, precision, and safety, reducing the need for labor in repetitive and potentially dangerous jobs. Several companies mention the implementation of robotics in their production lines, such as Interviewee #6, #5 and #9.
- Digitalization: The digitalization of processes, such as the creation of 3D models of blocks and parts, allows for the optimization of cutting, waste reduction, and product customization. Interviewee #6 highlights the importance of 3D scanning for the future of the industry, while Interviewee #9 mentions the implementation of an ERP that allows tracking the entire production process.
- Internet of Things: IoT enables the connection between machines and systems, allowing real-time data collection on production performance, energy consumption, and other relevant parameters. Interviewee #10 mentions the acquisition of energy meters to monitor the consumption of each machine.
- Data Analysis: The analysis of large datasets (Big Data) allows for the identification of patterns and trends, optimizing decision-making in areas such as inventory management, production planning, and preventive maintenance. Interviewee #2 highlights the importance of using data for informed decision making.

4.2.2 Mapping Results to SCOR Model Processes

The SCOR provides a comprehensive framework for analyzing, modeling, and improving supply chain processes that can be used in one key element that all interviewed companies lacked: strategic benchmarks that measure how successful the implementation of I4.0 tools have been in their business.

The framework six main processes - Plan, Source, Make, Deliver, Return, and Enable - can be directly related to the stages of the OS industry value chain, from quarry extraction to final product delivery to the customer (APICS, 2017).

The **Planning** stage forms the strategic foundation of an efficient and responsive I4.0 enabled supply chain. Central to effective planning is the leveraging of Data Analysis and robust Decision-Making tools. The strategic deployment of data analysis and business intelligence (BI) software empowers organizations to move beyond reactive approaches to proactive and predictive planning. For example, by analyzing vast datasets from across the value chain, these tools enable companies to make more informed decisions across critical planning domains, including production scheduling, optimized inventory management, and accurate demand forecasting. This data-driven approach minimizes guesswork, reduces uncertainty, and allows for agile adjustments to market fluctuations and evolving customer needs.

Integrating a comprehensive ERP system enables the seamless management of all sides of the business, from finance and procurement to production and distribution, all in real-time. This gives a whole view across the enterprise eliminating data silos, fostering cross-functional collaboration, providing a single source of truth for informed decision-making at all levels. As Interviewee #5 powerfully illustrates, their company successfully implemented an ERP system to manage all value chain processes, streamlining each process into a linked one. This story highlights the transformative potential of ERP in creating a cohesive and efficient operational ecosystem.

Data analysis and ERP systems are not merely supportive tools within this stage; they are essential enablers for achieving SCOR's planning objectives, specifically, these technologies fundamentally enhance the ability to accurately forecast demand, optimize resource allocation across the supply chain, and engage in effective strategic planning. By providing granular insights into historical trends, real-time market signals, and operational performance data, these tools can empower OS companies to develop more accurate demand predictions, strategically allocate resources to meet anticipated needs, and formulate robust long-term strategies that align with overall business objectives.

Within the **Sourcing** stage, the integration of advanced digital technologies is vital to optimize operational efficiency and ensure robust inventory management, specifically, the strategic deployment of Radio-Frequency Identification (RFID) tags and Quick Response (QR) codes to provide granular traceability for raw materials, from the quarry of origin to the processing factory. This system facilitates a transparent and accountable supply chain, enabling precise tracking of individual blocks throughout the initial supply stages.

Complementing this enhanced traceability, the utilization of IoT sensors, alongside technologies like drones and 3D scanners, brings real-time data acquisition regarding resource quality and quantity. The interconnected sensors can continuously monitor key metrics in situ, providing immediate insights into available rock volume, structural integrity, and other critical quality parameters. This wealth of dynamic data empowers stakeholders to make informed, agile decisions regarding extraction strategies, resource allocation, and overall sourcing optimization.

This technological advancement aligns with broader industry trends toward digitalization, mirroring the experiences of leading organizations. As exemplified by operations detailed by Interviewee #7, who leverages a digital platform to meticulously record machine maintenance and fuel consumption, the sector is increasingly adopting data-driven approaches to enhance productivity and control costs. The implementation of RFID, QR codes, and IoT sensors in sourcing represents a similar strategic move, extending digital visibility directly into the raw material supply chain.

From a SCOR model perspective, these technologies offer substantial improvements across several key dimensions. Firstly, enhanced supplier selection becomes possible through the aggregation of performance data related to material provenance, delivery timelines, and adherence to quality standards, all captured via the digital tracking system. Secondly, procurement processes are streamlined and optimized; real-time inventory visibility and demand forecasting, facilitated by IoT sensor data, enable more efficient purchasing decisions and reduce the risk of stockouts or overstocking. Finally, and perhaps most critically, inventory control is significantly enhanced. The accurate and continuous tracking of materials minimizes discrepancies, reduces manual inventory checks, and provides a robust foundation for optimized stock levels and just-in-time material flow strategies

In the critical **Make** stage, advanced manufacturing technologies are transformative. The strategic implementation of robotics, automation, and CNC machines fundamentally reshape production paradigms. CNC machines, with their inherent precision and repeatability, ensure consistently high-quality components, while robotic systems and automated cutting systems further amplify these benefits, increasing production speed and overall efficiency while simultaneously minimizing human error. This collaborative combination empowers Portuguese OS companies to move beyond standardized outputs towards mass customization, responding effectively to diverse market demands and niche product specifications without sacrificing production volume or lead times.

Integral to this enhanced production environment is the incorporation of sophisticated quality assurance mechanisms. Sensors and machine vision systems can be deployed throughout the manufacturing process to continuously monitor product characteristics and detect even minute deviations from pre-defined specifications. This real-time defect detection capability is crucial for proactive quality management, enabling immediate corrective actions, significantly reducing rework, minimizing waste, and ensuring consistently high product standards.

These technological advancements are not merely theoretical improvements but are actively being implemented and yielding tangible results in in the industry. As Interviewee #9 highlights, through their investment in automated production lines featuring robots, they have successfully reduced labour needs and increased production speed. This real-world example underscores the practical benefits and competitive advantages attainable through the adoption of these advanced manufacturing technologies. Furthermore, the utilization of 3D modelling throughout the design and manufacturing process enables virtual prototyping, process simulation, and intricate component design, contributing to both enhanced product functionality and optimized manufacturing workflows.

Manufacturing efficiency is dramatically improved through increased speed, reduced labor costs (as demonstrated in the example), and optimized resource utilization. Product quality is enhanced through precision manufacturing, real-time defect detection, and reduced variability, leading to higher customer satisfaction and reduced warranty claims. Finally, customization capabilities are significantly expanded, allowing for greater product differentiation, responsiveness to evolving market trends, and the ability to cater to specialized customer requirements

The **Deliver** stage is significantly enhanced through the strategic application of digital platforms and interconnected technologies. ERP systems with logistics and transportation platforms creates a unified digital ecosystem, enabling real-time order tracking and delivery optimization. This seamless data exchange across systems provides unparalleled visibility into the shipment lifecycle, from dispatch to final destination, allowing for proactive management of potential delays and efficient resource allocation.

Furthermore, the implementation of AGVs between shopfloor and warehouse and distribution centers streamlines the internal transport of finished products. AGVs, often equipped with IoT sensors, optimize material flow, reduce manual handling, and contribute to faster order processing times. These sensors can also provide valuable data on AGV performance, route optimization, and potential bottlenecks within the internal delivery process, further refining operational efficiency.

Extending the digital reach to the customer interface, online marketplaces and company websites become powerful tools for enhancing the customer experience. Featuring interactive digital catalogs and 3D visualizations of stone slabs, these platforms empower customers to make informed purchasing decisions. The ability to virtually explore product options, visualize materials in different contexts, and access detailed specifications significantly enhances customer choice and facilitates a more engaging and satisfying purchase journey. It also expands the footprint of Portuguese OS companies, allowing them to show their products globally in a way that was not possible before.

In the **Return** stage, it is necessary a robust and efficient returns management systems. These systems are not simply about processing returned items; they are fundamental to minimizing financial losses, controlling operational costs and maintaining customer goodwill. Effective returns management enables the fast and efficient processing of returned products, as originally stated, directly minimizing losses and costs associated with reverse logistics. This streamlined handling reduces the time products spend in the return pipeline, freeing up inventory, and allowing for quicker decisions regarding refurbishment, resale, or responsible disposal.

Beyond mere efficiency, well-designed returns management systems are integral to a broader operational strategy. They provide valuable data insights into product quality issues, common reasons for returns, and potential areas for process improvement in earlier stages of the supply chain – from sourcing and manufacturing to delivery. This data-driven feedback loop can inform product design enhancements, packaging improvements, and refined quality control measures, ultimately reducing future return rates.

The successful deployment and sustained effectiveness of I4.0 initiatives hinge critically on the **Enable** stage. This stage recognizes that technology adoption is not solely about infrastructure and software, but also mainly about human capital. The sophisticated technologies behind I4.0 – from advanced robotics to complex data analytics platforms – need a highly skilled workforce capable of not only operating but also maintaining and optimizing these advanced systems. Without a competent and adaptable workforce, the potential benefits of I4.0 remain largely unrealized.

Therefore, a strategic investment in training and reskilling programs is an important step for organizations embarking on their I4.0 journey. These programs must be continuous and comprehensive, designed to update employees' skills to meet the evolving demands of technology-driven operations. This includes adopting digital literacy, developing expertise in data analysis, and building skills in managing automated systems. Furthermore, as Interviewee #10 aptly pointed out the necessity of several training courses to overcome resistance to I4.0 tools, it is crucial to recognize and address the change management aspect of workforce transformation. Training must not only impart technical skills but also cultivate a culture of digital fluency and embrace innovation among employees.

Partnerships between companies, universities, specialized training institutions, and technology providers are fundamental. These collaborations facilitate knowledge sharing, accelerate the development of new technologies tailored to specific industry needs, and collectively contribute to the creation of a vibrant innovation ecosystem. Universities and research institutions offer cutting-edge knowledge and research capabilities, while technology providers bring practical implementation. Industry-wide collaboration ensures that best practices are disseminated, and workforce development efforts are aligned with the evolving technological landscape.

4.2.3 Measuring Success with SCOR Metrics

Measuring the success of I4.0 integration into Portuguese OS industry can be done through specific KPIs that cover the economic, environmental, and social dimensions of sustainability:

- Economic: Reduction of production costs, increased productivity, inventory optimization, and improved profitability.
- Environmental: Reduction of energy and water consumption, reduction of greenhouse gas emissions, waste minimization, and promotion of the circular economy.
- Social: Improvement of working conditions, increased worker safety, workforce skills development, and promotion of social inclusion.

Companies can use the SCOR model KPIs, adapting them to their specific reality. Some important metrics include:

- Efficiency: Production cycle time, material utilization, energy consumption, production costs.
- Quality: Defect rate, number of customer complaints, compliance with specifications.
- Sustainability: Carbon footprint, water consumption, use of recycled materials, environmental impact of extraction.
- Profitability: Profit margin per piece produced, return on investment in technology.

The interviewees revealed that the Portuguese OS industry faces challenges in implementing I4.0, such as investment costs, lack of skilled labor, resistance to change, and a culture of competition that limits collaboration between companies. However, there are also significant opportunities:

- Government Support: Portugal has access to community funds that can finance investments in technology and innovation.

- Collaboration with Universities: Partnerships with universities can provide access to research and development of new technologies and solutions.
- Growing Awareness: The importance of sustainability and digitalization is increasing, driving the industry to adopt new practices.

In the end, by seizing opportunities and overcoming challenges, the Portuguese OS industry can leverage I4.0 technologies in the SCOR model to drive innovation, sustainability, and competitiveness in the global market.

CHAPTER 5. CONCLUSION

5.1 Final Conclusions

The Portuguese OS sector is a high value added, export driven industry that simultaneously faces pressing sustainability challenges and a need for greater operational efficiency. This research aimed to explore how I4.0 technologies can be connected—through the SCOR model—to drive both innovation and sustainability in the sector.

Through a qualitative, interview based study of key industry stakeholders, the following insights emerged:

1. Relevant I4.0 technologies – IoT enabled sensors, digital twins, advanced data analytics, cloud based ERP systems, and collaborative robotics were identified as the most impactful tools for the OS value chain. Their greatest contribution lies in real time monitoring of quarry extraction, energy intensive processing, and logistics, thereby enabling predictive maintenance, waste reduction, and optimized resource allocation.

2. Critical success factors & best practices – Strong top management commitment, cross-functional digital literacy, and clear alignment of I4.0 initiatives with sustainability targets (e.g., reduced water/energy consumption, lower CO2 emissions) proves to be decisive. Successful projects combined incremental pilots with a robust change management program and leveraged public private partnerships (e.g., with research institutes and technology providers).

3. Integration into the SCOR model – Mapping interview findings onto the six SCOR processes (Plan, Source, Make, Deliver, Return, Enable) revealed concrete entry points:

- Plan – demand forecasting enriched by AI driven analytics;
- Source – supplier portal integration and blockchain based traceability;
- Make – digital twins for quarry to slab transformation, enabling "what if" scenario testing;
- Deliver – IoT tracked fleet management and route optimisation;
- Return – closed loop material tracking for circular economy waste reuse;
- Enable - strategic investment in training and reskilling and partnerships with key stakeholders.

4. Performance measurement – Traditional SCOR metrics (e.g. inventory turns) remain useful but must be complemented with sustainability KPIs such as energy intensity per tonne of processed stone, water use efficiency, and carbon footprint per unit shipped.

Overall, the study demonstrates that a systematic, SCOR guided deployment of I4.0 technologies can simultaneously raise productivity, lower operating costs, and meet increasingly stringent EU and national sustainability regulations. By doing so, Portuguese ornamental stone firms can preserve their competitive advantage in global markets while contributing to the UN's SDG (such as SDG 9 – Industry, Innovation and Infrastructure, and SDG 12 – Responsible Consumption and Production).

Table 5.1: Summary of results

Category	Results
RQ1: Relevant Industry 4.0 Technologies	**Robotics and Automation:** Increase efficiency, reduce labour dependence, and improve product quality. Challenges include investment costs and process adaptation. **Digitalization:** Crucial for modernizing processes, from stock management to order tracking. ERP software is essential for real-time monitoring and integration. **CNC Machines and 3D Modelling**: Widely used for mass customization and precision. 3D scanners help create detailed designs and optimize material use. **Internet of Things (IoT):** Potential to revolutionize the industry by collecting real-time data to optimize production and reduce waste. However, its adoption is still limited.
RQ2: Key Success Factors and Best Practices	**Strategic Vision:** Companies need a long-term vision aligning with customer priorities and sustainability goals. **Skilled Workforce**: Recruitment, training, and continuous upskilling are vital. Overcoming resistance to change, especially among older employees, is crucial. **Collaboration**: Partnerships with universities and technology providers drive innovation. Participation in R&D projects is common. **Best Practices**: Include digitalization, automation, traceability, sustainability, continuous training, data analysis, and transparent communication. **Barriers**: High initial costs, resistance to change, lack of skilled professionals, and industry fragmentation.

RQ3: Effective Integration and Success Measurement	**ERP Systems**: Streamline business processes and enable real-time monitoring from extraction to final delivery. **3D Modelling and Scanners:** Facilitate production planning and material optimization. **Robotics and Automation**: Increase efficiency and productivity in key processes. **IoT Sensors**: Collect real-time data to identify inefficiencies and optimize processes. **Success Metrics**: Currently lacking standardized metrics. Suggested KPIs include productivity, efficiency, sustainability, quality, and profitability.
Discussion	**Relevant Technologies:** Robotics, digitalization, IoT, data analysis. **SCOR Model**: Provides a framework for analysing and improving supply chain processes. Can help establish strategic benchmarks for measuring the success of I4.0 integration. **Challenges and Opportunities**: High investment costs, lack of skilled labour, and resistance to change are significant challenges. Opportunities include government support, collaboration with universities, and growing awareness of sustainability

5.2 Work limitations and future work

The research provides valuable insights, yet several constraints limit the generalizability of its findings. The geographic scope is confined to the Portuguese OS industry, meaning that the results may not translate directly to stone sectors in other countries.

The sample size and composition consist of twelve semi-structured interviews with senior managers and technical experts and, although thematic saturation was achieved, further sample interviews with different stakeholders would add more insights to the research.

The temporal horizon of the study spans 2024–2025, a period of rapid technological evolution; emerging technological evolutions that were not yet widely adopted could alter the relevance of the identified success factors.

For future work, it is recommended to follow up with the practical implementation of the SCOR model process and KPIs in a company to gather practical insights and validate the findings of this research. Additionally, it would be interesting to explore whether the findings can also be applied to other industries that face similar challenges.

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CHAPTER 7. Appendix

Appendix A: Interview Questions

- **Industry 4.0 general knowledge**

1. Can you explain, in simple terms, what Industry 4.0 is and what are its main concepts and associated technologies?

2. What are the advantages of using I4.0 technologies?

- **Company context with Industry 4.0**

3. Have any investments in I4.0 technologies been made in your company?

4. What are the main drivers for implementing i4.0 technologies?

5. What impacts did/would the use of these technologies have? What benefits?

6. What challenges or risks did your company encounter when adopting i4.0 technologies? How are you overcoming them?

7. How do you measure the impact and success of i4.0 technology implementations? Do you have performance metrics and KPIs to measure them in terms of efficiency, sustainability and overall business performance?

- **Challenges and External Factors**

8. What are the main challenges your company faces in terms of sustainability? Are there specific regulatory challenges that your company faces in this regard? How can Industry 4.0 contribute to sustainability and reducing environmental impact?

9. Do you consider that there are necessary skills in HR to face the challenges of I4.0? Which ones do you consider to be the most important? Was it necessary to do training?

10. To what extent is collaboration between companies, universities or other institutions important for the successful adoption of Industry 4.0? Does your company have such partnerships? Can you specify?

- **Portuguese Ornamental Stone Industry and I4.0 Impacts**

11. What are the critical factors for the success of Industry 4.0 in the OR sector? What are the main barriers to the integration of these technologies? How can they be overcome?

12. What specific performance indicators do you consider most relevant to monitor and measure the results achieved within the OR sector?

13. Within the OR sector, at what level do you consider your company to be in terms of implementing i4.0 technologies? Consider a scale of 1 to 5, where 1 indicates "not implemented at all" and 5 "fully implemented".

14. What do you consider to be the state of implementation of I4.0 in the Portuguese OR industry and what do you predict that same state will be in 3 years? Consider a scale of 1 to 5, where 1 indicates "not implemented at all" and 5 "fully implemented".