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Master in Engineering for Direct Digital Manufacturing

Carlos Eduardo Cremonini

Leiria, September of 2023

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Project under the supervision of Professor Doctor Joel Oliveira Correia Vasco and Professor Doctor Marcelo Rudolfo Calvete Gaspar

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This dissertation/project report is original, made only for this purpose, and all authors whose studies and publications were used to complete it are duly acknowledged.

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Abstract

The rapid evolution of Industry 4.0 technologies has ushered in a new era in manufacturing systems, with Digital Twins leading the way. These virtual replicas offer invaluable opportunities for simulating and optimizing new manufacturing processes, and their most transformative impact may lie in the creation of these digital models. This research unifies the main key concepts of four separate studies, all of which explore the application of Digital Twins in the ornamental stone industry.

Industry 4.0 systems and their technologies have directly influenced the ornamental stone industry, addressing both the effects on mineral resources and energy consumption in daily operations. In addition, research and development initiatives seek to make this industry more efficient and sustainable, addressing crucial issues such as economic growth, environmental impact, and social welfare. The increasing digitization of manufacturing systems and their integration with digital models has played a key role in this process, enabling the replication of shop floor operations and the optimization of material use.

The application of Digital Twins, which are virtual replicas of physical systems, has been explored in an ornamental stone manufacturing company. These digital models have demonstrated the ability to save time and resources during prototype design, as well as offering continuous diagnostics and optimization throughout production. It is important to note that the implementation of Digital Twins requires care due to technical challenges, but their adoption promises to significantly impact business value, despite the initial complexities.

Managing stone cutting devices with Digital Twins presents real challenges in the ornamental stone industry, but it also paves the way for greater precision, efficiency, and cost savings. These digital models enable real-time monitoring, predictive maintenance, and virtual simulations. This study explores different approaches to connecting physical cutting machines to their respective Digital Twins, evaluating criteria such as communication speed, security, scalability, and cost. The results of this analysis provide valuable information for implementing Digital Twins in the stone cutting industry.

Keywords: Manufacturing systems integration, Sustainability, Digital Twins, Applications, Ornamental Stone Sector, Security&Reliability

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Resumo

A rápida evolução das tecnologias da Indústria 4.0 inaugurou uma nova era nos sistemas de fabrico, com os Digital Twins à frente desse avanço. Essas réplicas virtuais oferecem oportunidades inestimáveis para simulação e otimização de novos processos de fabrico, sendo que seu impacto mais transformador pode residir na criação desses modelos digitais. Esta pesquisa unifica os principais conceitos-chave de quatro estudos distintos, todos eles explorando a aplicação dos Digital Twins na indústria da pedra ornamental.

Os sistemas da Indústria 4.0 e suas tecnologias têm influenciado diretamente a indústria da pedra ornamental, abordando tanto os efeitos sobre os recursos minerais quanto o consumo de energia nas operações diárias. Além disso, iniciativas de pesquisa e desenvolvimento buscam tornar essa indústria mais eficiente e sustentável, abordando questões cruciais, como crescimento econômico, impacto ambiental e bem-estar social. A crescente digitalização dos sistemas de fabrico e sua integração com modelos digitais têm desempenhado um papel fundamental nesse processo, permitindo a replicação das operações de chão de fábrica e a otimização do uso de materiais.

A aplicação dos Digital Twins, que são réplicas virtuais de sistemas físicos, tem sido explorada em uma empresa de fabricação de pedra ornamental. Esses modelos digitais demonstraram a capacidade de economizar tempo e recursos durante o projeto de protótipos, além de oferecer diagnósticos contínuos e otimização ao longo da produção. É importante notar que a implementação dos Digital Twins requer cuidados devido a desafios técnicos, mas sua adoção promete impactar significativamente o valor dos negócios, apesar das complexidades iniciais.

A gestão de dispositivos de corte de pedra com Digital Twins apresenta desafios reais na indústria da pedra ornamental, mas também abre caminho para uma maior precisão, eficiência e economia de custos. Esses modelos digitais possibilitam o monitoramento em tempo real, manutenção preditiva e simulações virtuais. Este estudo explora diferentes abordagens para conectar máquinas de corte físicas a seus respectivos Digital Twins, avaliando critérios como velocidade de comunicação, segurança, escalabilidade e custo. Os resultados dessa análise fornecem informações valiosas para a implementação de Digital Twins na indústria de corte de pedra.

Palavras-chave: *Integração de Sistemas de Fabrico, Sustentabilidade,* Digital Twins*, Aplicações, Setor da Rocha Ornamental, Segurança&Confiabilidade*

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Contents

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List of acronyms

AI	Artificial Intelligence
ESTG	*Escola Superior de Tecnologia e Gestão*
IIoT	Industrial Internet of Things
IoT	Internet of Things
IPLeiria	*Instituto Politécnico de Leiria*
MQTT	Message Queuing Telemetry Transport
OPC	Open Platform Communications
OPC-UA	Open Platform Communications Unified Architecture
VPN	Virtual Private Network

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1. General Context

The ornamental stone industry in Portugal faces significant challenges related to operational efficiency, sustainability, and economic growth. To overcome these challenges, the application of Industry 4.0 and Digital Twin technologies has stimulated interest. In this research, the potential of these technologies was addressed, analyzing their contribution to improving the ornamental stone industry and boosting its sustainable growth. Through the articles presented in this project, the goal is to provide valuable insights for companies and professionals interested in the digital transformation of the sector [1].

In this context, the InovMINERAL4.0 project stands out as an innovative initiative that aims to boost the technological development and competitiveness of ornamental stone companies in Portugal. The project is a sequel of previous successful projects such as Jetstone, InovSTONE and InovSTONE4.0, which played a key role in advancing the industry and the adoption of modern technologies. Jetstone focused on improving the processes of extraction, transformation, and marketing of ornamental stones. By implementing innovative practices and advanced technologies such as automation and robotics, the project managed to increase operational efficiency, reduce costs, and improve product quality [1].

InovSTONE has expanded its technological horizons even further, focusing on digitization and the creation of digital twins to optimize the management of production processes and decision-making. This approach has enabled accurate real-time simulation of operations, making it easier to identify blockages and implement improvements. InovSTONE4.0, meanwhile, explored the possibilities offered by Industry 4.0, promoting the integration of technologies such as IoT, Big Data and artificial intelligence. This resulted in greater process automation, more flexible and adaptable production lines, and the implementation of remote monitoring and predictive maintenance solutions [2], [3].

The contribution of these projects to the technological development and competitiveness of ornamental stone companies in Portugal has been remarkable. The adoption of advanced technologies has driven the evolution of the industry, allowing for greater efficiency, improved quality, and more sustainable practices. In addition, these projects have stimulated collaboration between companies, universities, and research centers, promoting the transfer of knowledge and the training of professionals in the sector. This has resulted in a more innovative industry, capable of facing global challenges and conquering new markets [4].

The InovMINERAL4.0 project is therefore a natural continuation of this digital transformation movement and aims to further boost the ornamental stone industry in Portugal. With the application of advanced technologies, it is hoped to achieve significant gains in productivity, energy efficiency, sustainability, and international competitiveness, consolidating Portugal as one of the main players in this constantly evolving sector [1].

The natural stone sector has long been an intrinsic part of the construction and design industry, providing materials for everything from historic monuments to modern industrial facilities. However, like many other industrial sectors, it faces several challenges ranging from operational efficiency to environmental sustainability. It is against this scenario that the InovMINERAL4.0 project is set to revolutionize the natural stone sector in Portugal through the integration of Industry 4.0 technologies [4].

Industry 4.0 is not just a dying fad, it is a paradigm shift that promises to transform the way industries operate. With the integration of cyber-physical systems, the Internet of Things (IoT), Artificial Intelligence (AI) and data analysis, Industry 4.0 offers a unique opportunity to optimize operations, improve quality and increase efficiency. However, adopting these technologies is not without its challenges. It requires a deep understanding of industrial processes, as well as a well-planned strategy for implementing new Technologies [3].

This is where the concept of digital twins comes into play. A digital twin is a virtual representation of a physical object or system. It serves as a mirror of the real world, providing a platform for simulation, analysis, and control. In the context of the natural stone sector, digital twins have the potential to radically transform the way operations are carried out. They can be used to simulate the stone cutting process, optimize logistics and even for advanced technical training [5].

Technical training is an area that is often overlooked in discussions about Industry 4.0. However, it is a critical component for the success of any technological initiative, it must consider several factors, including operator safety, the integrity of the equipment and the effectiveness of the training process itself. Furthermore, in an increasingly globalized world, it is often necessary to provide remote training, which brings its own set of challenges and complexities [6].

This work addresses all these issues comprehensively. It not only provides a roadmap for implementing Industry 4.0 technologies in the natural stone sector, but also serves as a case study for other industries looking to do the same. Through a series of initiatives, from the optimization of the stone cutting process to the development of advanced technical training systems, the work demonstrates how the successful integration of new technologies can result in significant improvements in efficiency, quality, and sustainability [3], [4].

The work also highlights the importance of interdisciplinary collaboration. The successful implementation of Industry 4.0 technologies requires a multi-faceted approach involving specialists in engineering, computer science, industrial design, and many other disciplines. It is only through such collaboration that we can hope to solve the complex challenges that Industry 4.0 presents [3].

Ultimately, this work serves as a model for the future, not just for the natural stone sector, but for the industry. It demonstrates that with the right strategy, the right institutional support, and a collaborative approach, it is possible to turn the challenges of Industry 4.0 into opportunities for innovation and growth [3].

1.1. Objectives and motivations for the work

The main objectives of this research are:

- Analyze the current state of the art on the ornamental stone industry in Portugal: Understand the challenges and opportunities facing the sector, especially in terms of operational efficiency, quality, and sustainability [1].
- Explore the potential of industry 4.0: Investigate how Industry 4.0 technologies, such as digital twin, can be applied to improve industrial processes in the ornamental stone sector [4].
- Develop and implement digital twins: Create digital models that simulate processes and operations in the ornamental stone industry, with the aim of optimizing production and reducing waste [5].
- Evaluating the impact of new technologies: Measuring the tangible benefits of technological implementations in terms of efficiency, cost, and sustainability [7].
- Promote advanced technical training: Use digital twins and other Industry 4.0 technologies to develop training programs that prepare the workforce for the new industrial era [4].
- Fostering interdisciplinary collaboration: Establishing partnerships with academics, industry professionals and other stakeholders to promote innovation and technological development in the sector [1].
- Contribute to academic literature: Publish research results in high-impact scientific journals and conferences, providing valuable insights for future research in the field [8].

The main reasons for this research are:

- Need for innovation: The ornamental stone industry is traditional and often resistant to change. The need for innovation is imperative to remain competitive in a global market [1], [4].

- Sustainability: With the growing environmental challenges, finding ways to make the industry more sustainable is not only desirable, but essential [7].

- Economic development: The ornamental stone industry is one of the main contributors to the Portuguese economy. Improving its efficiency and competitiveness has direct implications for the country's economic development [9].

- Personal interests: As an engineer by training, the author has a keen interest in how new technologies can be applied to solve real problems in industrial sectors [3].

- Legacy of previous projects: The success of the Jetstone, InovSTONE and InovSTONE4.0 projects are additional motivation to continue exploring new technological frontiers in the ornamental stone industry [2].

- Academic and professional contribution: This work serves as an opportunity to contribute to both the academic field and industry by providing a comprehensive study that can serve as a guide for future research and practical implementation [8].

1.2. Document Organization

This project is structured to provide an in-depth and comprehensive understanding of the application of Industry 4.0 and Digital Twin technologies in the Portuguese ornamental stone industry. The document is organized as follows:

1. General Context

    1.1. Objectives and motivations for the work

    1.2. Organization of the Document

2. General Introduction

3. Conference paper (1) - "INDUSTRY 4.0 CONCEPT IN THE PORTUGUESE NATURAL STONE CLUSTER", presented and published on the Global Stone Congress 2023, June 18th -23rd, Batalha, Portugal.

This chapter introduces the fundamental concepts of Industry 4.0 and its relevance to the ornamental stone industry in Portugal. The first article is the starting point, introducing the fundamental concepts of Industry 4.0. It sets the scene for the subsequent discussion, providing a solid foundation of knowledge that allows the reader to understand the motivations and challenges associated with adopting these emerging technologies.

4. Conference paper (2) - "DIGITAL TWINS AND THE ORNAMENTAL STONE INDUSTRY: KEY FACTORS", presented and published on the Global Stone Congress 2023, June 18th -23rd, Batalha, Portugal.

Here, the emphasis is on the application and benefits of Digital Twins, demonstrating how they can revolutionize production and sustainability in the sector. The second article, focused on the Digital Twins, acts as a catalyst for further discussion on specific technologies that have the potential to revolutionize the industry. It not only highlights the practical benefits, such as efficiency and sustainability, but also addresses the technical complexities involved in implementing these digital solutions.

5. Book Chapter (3) - "DESIGN AND IMPLEMENTING OF A DIGITAL TWIN FOR A STONE-CUTTING MACHINE: A CASE STUDY", presented and published on the Proceedings of 5th International Conference on Industry 4.0 and Smart Manufacturing

This book chapter delves into the practical implementation of Digital Twins, analyzing connection options and the technical and financial implications of adopting them. The third article takes the discussion one step further, digging into the technical and practical details of implementing a Digital Twin in a real industrial environment. It offers a granular view of the considerations that must be made, from technology selection to financial implications, thus providing a practical guide for companies and industry professionals.

6. Research Paper (4) - "A DIGITAL TWIN-BASED MANUFACTURING SYSTEM FOR ADVANCED TECHNICAL TRAINING", submitted at 15th September 2023 to the International Journal of Advanced Manufacturing Technologies (Manuscript Number: JAMT-D-23-04325, available in the attached appendix).

The focus of this paper is the use of Digital Twins for advanced technical training, demonstrating how these technologies can be used to train the next generation of industry professionals. The fourth and final article completes the narrative arc, exploring how Industry 4.0 technologies and Digital Twins can be applied in an educational context for advanced technical training. This focus on education and training highlights the importance of preparing the workforce for the demands of a rapidly evolving industry, closing the discussion loop by connecting technology, industrial practice, and human development.

7. Overall Conclusion

The sequence of the articles has been meticulously chosen to create a coherent and progressive narrative that reflects the complexity and multifaceted nature of digital transformation in the ornamental stone industry. This organization not only facilitates a smooth transition between topics, but also ensures that each article builds on the previous one, creating a solid and logical argumentative structure. The result is a project that offers the reader a holistic and well-founded view of the relevance, applicability, and potential of Industry 4.0 technologies in the ornamental stone industry.

2. General Introduction

The industrial revolution 4.0 has catalyzed significant changes across various industries, and the natural stone sector is no exception. This sector, particularly prominent in Portugal, is at a pivotal juncture where the adoption of emerging technologies could redefine its future. The InovMINERAL4.0 project serves as a groundbreaking initiative aiming to integrate Industry 4.0 concepts into the Portuguese natural stone cluster, setting the stage for this paper [4].

One of the most pressing challenges facing the Portuguese natural stone sector is the inefficiency and lack of precision in cutting and finishing processes. These inefficiencies not only escalate operational costs but also compromise the quality of the product. This paper aims to tackle this specific challenge by investigating the feasibility and implementation of a digital twin for stone cutting machines within the Portuguese natural stone cluster [4], [5].

Addressing this issue is not just a technological challenge but a necessity for enhancing the competitiveness and sustainability of the Portuguese natural stone industry. Current inefficiencies result in resource wastage and diminished profitability, making it imperative to explore innovative solutions like digital twins [1].

The primary objective of this paper is to outline a comprehensive strategy for the successful deployment of a digital twin in the Portuguese natural stone sector. This strategy focuses particularly on optimizing cutting and finishing processes. The approach will be validated through a case study, which will not only demonstrate the technical feasibility but also highlight the challenges, best practices, and key considerations for successful implementation [4].

Industry 4.0 is not merely a buzzword, but a paradigm shifts that fuses physical and digital elements to create intelligent, autonomous systems. It involves the integration of various technologies like sensors, IoT, AI, among others, to enhance efficiency, quality, and sustainability. However, the adoption of these technologies is fraught with complexities, requiring a deep understanding of various factors that can make or break these initiatives [7].

A digital twin serves as a virtual replica of physical systems, enabling real-time simulations, analyses, and optimizations. In the context of the ornamental stone sector, digital twins can simulate the cutting and finishing processes, thereby allowing operators to preemptively identify and rectify issues. This not only streamlines operations but also minimizes waste and elevates the quality of the final product [4].

However, the implementation of a digital twin is far from straightforward. It demands a robust IT infrastructure and a nuanced understanding of the machine or process being modeled. This paper will delve into a case study involving the design and implementation of a digital twin for a stone cutting machine, offering insights into the challenges of real-time data management, system integration, and ensuring security and reliability [10].

In addition to process optimization, Industry 4.0 also underscores the importance of advanced technical training. The most sophisticated technologies are futile if the workforce lacks the skills to operate them effectively. Digital twins can serve as potent training platforms, allowing operators and technicians to acquaint themselves with new systems in a risk-free environment [3], [5].

Advanced technical training involves more than just skill transmission; it demands a holistic approach that considers adequate preparation, the adoption of state-of-the-art technologies, and adherence to best practices. This is particularly crucial in industrial settings where the margin for error is minimal, and the repercussions of mistakes can be severe [3].

The successful incorporation of Industry 4.0 concepts into the natural stone sector is a multifaceted endeavor. This paper aims to serve as a comprehensive guide for this intricate integration, covering aspects ranging from process and system optimization to advanced technical training. As the industry transitions into a more digitized era, the proper implementation and understanding of digital twins will be pivotal for maintaining competitiveness and fostering innovation [4].

3. INDUSTRY 4.0 CONCEPT IN THE PORTUGUESE NATURAL STONE CLUSTER

The first article of this project serves as a fundamental starting point for a series of investigations on the implementation and impact of Industry 4.0 in the ornamental stone sector in Portugal. This chapter aims to provide a comprehensive analysis that addresses not only the technological challenges and opportunities associated with the adoption of these emerging technologies, but also their impact on mineral resources and energy use in daily operations [4].

This study is especially relevant to establish a theoretical and practical context, introducing fundamental concepts such as Industry 4.0 and Digital Twin. These concepts are crucial for understanding the ongoing technological transformations in the ornamental stone sector and serve as the basis for subsequent articles exploring the application of Digital Twins and other technological advances in the sector [4], [5].

In addition to providing an overview of Industry 4.0 systems and technologies, this chapter also acts as a specific case study for the natural stone cluster in Portugal. This approach not only highlights the technological innovations that are reshaping the industry, but also offers valuable insights that can be applied to other traditional sectors in the process of modernization [4].

The chapter will also address research and development initiatives that enable ornamental stone industries to be more efficient and sustainable, addressing important issues such as economic growth, environmental impact, and social welfare. These developments are integrated with the increased digitalization of manufacturing systems and their integration with discrete and numerical models to replicate shop floor operations [1].

The unique situation of the ornamental stone industry in Portugal is highlighted, and the resulting benefits are described and analyzed comprehensively, thus providing a complete picture of the implications and potential of Industry 4.0 in the Portuguese context [1], [4].

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INDUSTRY 4.0 CONCEPT IN THE PORTUGUESE NATURAL STONE CLUSTER

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Summary: *This research provides an overview of Industry 4.0 systems and technologies applied to the ornamental stone industry, focusing both on the effects on mineral resources and on the energy use in daily operation. Additionally, research and development initiatives that enable the ornamental stone industries to be more efficient and sustainable by addressing important issues such as economic growth, environmental impact, and social well-being are key to attain such objectives. Integral to these developments are the increasing digitalization of manufacturing systems and their integration with discrete and numerical models to replicate shop-floor operations. In addition, these technologies are essential for the efficient utilization of materials, be they raw materials or manufacturing instruments. The unique situation of the Portuguese ornamental stone industry is highlighted, and the ensuing benefits are described and thoroughly analysed.*

Key words: *Industry 4.0, Manufacturing systems integration, Mineral resources, Sustainability*

1. Introduction

With the current industry's ongoing digital transformation, the resulting increase in productivity and efficiency show to be the primary drivers of innovation and change across all sectors of our economy (Cheng et al., 2023; Du & Jiang, 2022).

Considering this impact, the European Union refers to the Industry 4.0 (I4.0) paradigm as the organization of production processes based on technology and devices autonomously communicating with each other along the value chain: a smart factory model of the future, using computer-driven systems to monitor physical processes, creating a virtual copy of the physical world, and making decentralized decisions based on self-organizing mechanisms (Ghobakhloo et al., 2021; Soori et al., 2023).

Such increasing digitalization of manufacturing industries in which physical objects are seamlessly incorporated into the information network, leads to production systems that are vertically networked with business processes within factories and enterprises and horizontally networked with spatially dispersed value networks that can be managed from the time an order is submitted through outbound logistics (Benitez et al., 2023; Z. Liu et al., 2022; Schubert et al., 2023).

2. The Industry 4.0 Paradigm

As a result of these developments, the distinction between industry and services becomes less significant, as digital technologies transform industrial products and services into hybrid products that are neither exclusively goods nor services. Indeed, both the Internet of Things and the Internet of Services are regarded as Industry 4.0 components (Malik et al., 2021; Peter et al., 2023; Pivoto et al., 2021).

Consequently, the key characteristics of Industry 4.0 paradigms (Nakagawa et al., 2021) can be summarized as follows:

- interoperability: the cyber-physical systems, such as work-piece carriers, assembly stations, and products, allow humans and smart factories to communicate with each outer and keep connected;
- virtualization: by connecting sensor data to simulation models and virtual plant models, this creates a virtual copy of the smart factory;
- decentralization: he capacity of cyber-physical systems to make autonomous decisions and produce locally using technologies like 3D printing;

- real-time capabilities: these abilities to acquire and analyze data enable immediate delivery of the derived insights;
- service orientation: the increased data and knowledge of the system allow for and increase focus on robust real-time services to be performed and provided;
- modularity: the individual module replacement or expansion enables smart factories' adaptability to variable demands.

In addition, quality and documentation requirements are increasing. Industry 4.0 is a new development in an industry that has revolutionized and digitized its various sectors. This new paradigm introduces a new industry concept, the smartification and digitization of factories, to create intelligent factories using connected devices, data analysis, and artificial intelligence technologies to automate processes (Ching et al., 2022; Stock & Seliger, 2016).

Industry 4.0, also known as the fourth industrial revolution, addresses these challenges by facilitating end-to-end communication between all production-relevant IT assets and production-relevant physical assets. According to this implementation strategy, the primary aims of Industry 4.0 (Antonino et al., 2019) may be highlighted as:

- IT systems vertical integration in production and automation engineering;
- horizontal integration of diverse IT systems across the value-chain;
- engineering consistency throughout the entire lifecycle;
- product customization by means of small quantities or even as a single lot size;
- new social infrastructures for work.

This approach of the Fourth Industrial Revolution and the current trend of automation technologies in the manufacturing sector is primarily related to significant recent enablers such as the cyber-physical systems (CPS), the Internet of Things (IoT), and cloud computing.

In the Industry 4.0 paradigm, embedded systems, semantic machine-to-machine communication, IoT, and CPS technologies are bridging the gap between the virtual and real worlds. In addition, a new generation of industrial systems related to smart reconfigurable machines and factories is emerging to manage the complexity of cyber-physical environment production systems (Morgan et al., 2021).

3. Recent Trends of the Ornamental Stone Sector

According to the United Nations, industrial development is essential for both income generation and the enhancement of living conditions (Navarrete et al., 2020). In turn, appropriate infrastructures provide facilities for industry and society, while innovation boosts technological capacities and leads to the development of new skills (De Andrade Régio et al., 2017; Régio et al., 2016). These factors are key for the Ornamental Stone Industry as is allows passing from a resource exploitation paradigm to a sustainable value-chain of natural resources to be efficiently integrated into modern practices and solutions.

3.1. Environmental sustainability vs. Economic growth

Integrating environmental sustainability with economic development and well-being is one of the greatest global challenges to reduce environmental degradation caused by economic growth and increase productivity (do more with less). Decoupling of resources and impacts is required to promote sustainable consumption and alter production paradigms, thereby facilitating the transition to a circular economy (Neves et al., 2020).

This integration is reinforced by two aspects: on the one hand, they are built slowly as the relationships between individuals share norms and mutual trust; on the other hand, they are also integrated with individuals from different spheres, but with common experiences. Such cooperation process includes a generalized incorporation of cross-fertilization of haves and have-nots, specifically technologies in the production and transformation processes, as well as the creation of suitable strategies for the production and promotion of Portuguese stone products, pre- and post-sale, support services, and internationalization (Carvalho et al., 2018a).

Much of this growth is related to the development model of the companies, *i.e.*, maturity is supported on a growth whose time assumes significant relevance. Particularly in Portugal, between the natural stone sector and the footwear industry a so-called cross-fertilization has recently taken place, *i.e.*, an exchange of knowledge between dedicated technologies of both sectors lead to mutual benefits and improvements. In this sense, the dynamics of cooperation between companies has been verified with significantly positive results, and its similarity with the evolution of the footwear sector should be highlighted (da Silva et al., 2020).

3.2. Mineral resources

It is acknowledged that for some nations with natural mineral resources, these assets are essential for promoting their sustainable development and, consequently, contributing to the growth of their economies (Dubiński, 2013). Furthermore, these mineral resources are regarded as nonrenewable natural resources, and they can be metallic (including iron, copper, tin, and lithium) or nonmetallic (quartz, limestone, marble, granite, ardosia, gypsum, sand, and coal). As for Portugal, many of the available nonmetallic minerals are mineral aggregates, and Portugal is abundant in terms of quantity, quality, and variety (Amorim Dinis & Sousa, 2003).

Materials used in applications of Industry 4.0 must be able to withstand the rigorous requirements. Novel applications require advanced composites and responsive (smart) materials that are compatible with emerging manufacturing technologies such as 3D printing and CNC machining. As a result of the significant progress in fields such as nanotechnology, these materials must have properties such as light weight and improved mechanical properties, as well as a sustainable production and general life cycle. In the context of circular economy, products made from these materials must be designed and manufactured with these factors in mind (Nascimento et al., 2019).

The potential of a nation's geological resources can be viewed as an economic development factor with increasing strategic significance and a strategic opportunity that should be leveraged (Ketels & Memedovic, 2008). Thus, representing an economic/political advantage for a country’s economic strategic mosaic, local mineral resources should allow for its global revenue and value creation (Andersson, 2020).

3.3. Energy usage and storage

The recent advancements in the energy sector, most notably on what concerns energy storage, smart infrastructure, and renewable energy, have had a significative impact on the fourth industrial revolution. A device (such as an automaton, drone, or wearable) that can only operate for a few minutes has limited utility. The advancements in energy storage technologies, such as batteries, enable industry 4.0 devices to operate long enough to be beneficial in their operating environment. On the other hand, the new information and communication technologies (ICT) introduced as part of Industry 4.0 have produced new energy distribution and management technologies (Tsaramirsis et al., 2022).

In the future decades, few other chemical elements will be as significant from an energy standpoint as lithium. Recently, lithium has become an essential component of battery electrolytes and electrodes, requiring a purity level of greater than 95.5%. Due to its low atomic mass, its charge and power-to-weight ratio is considerable. Lithium-ion batteries have the highest voltage and energy density of all rechargeable batteries and are favored for use in portable devices where high energy capability, low weight, and compact volume are essential (Heredia et al., 2020; Y. Liu et al., 2023).

4. I4.0 and the Portuguese Natural Stone Sector

4.1. Impact of the Portuguese Natural Stone Cluster

The growing need to access new markets and invest significantly in product, service, and process innovation leads to the formation of strategic alliances that can be crucial for a company's international operations. This can only be accomplished by exporting goods and/or services, or by physically entering the market in which it intends to operate.

Current companies should adopt networked business models, as there is a growing recognition that the peripheral technologies of one company are frequently the core activities of others. For cooperation to be effective, the parties involved must share the same values and pursue the same ends. The latter must be explicit, coherent, and motivating in addition to being realistic, consistent, hierarchical, and quantifiable.

In this context, specialized clusters (Ketels, 2011) consist of geographically-located groups of entities (companies and institutions) whose interconnections develop alongside relevant technological support and are founded on how the players manage to benefit from stakeholder relationships, sustain and strengthen competitive advantage, which is primarily due to three factors: (1) the interrelationships between the various participants; (2) the speed and ease of information and knowledge circulation; and (3) its accessibility.

Turning potential competitors into allies and suppliers of complementary products and services contributes to the development of new businesses, thus allowing for the neutralization of prominent rivals as threats and the creation of network economies by businesses with complementary assets.

These relationships are organized and focused on a thematic cluster, thus enhancing the performance of the companies, enhancing the competitive advantage of the members, fostering innovation, and attracting knowledge based on internal investment. Innovation occurs when those involved are in proximity, fostering the flow of information and the exchange of ideas. To such an end, the creation of a Mineral Resources cluster should be strongly committed to a partnership and network dynamics.

In 2009, the Portuguese Natural Stone Cluster was established to increase the national and international visibility of the country's Ornamental Rocks Sector and as a positioning tool for a group of companies involved in extraction, processing, and production of machinery and equipment under the VALORPEDRA project. Later, in February of 2017, the Cluster Portugal Mineral Resources was formally recognized as the new name.

The role of national universities has been fundamental in organizing the ideas that result in innovative and attractive projects in the Portuguese Mineral Resources cluster foster the attraction of companies to become more competitive and efficient. In this sense, the creation of an alliance with the purpose of overcoming the difficulties experienced in the Portuguese Stone Sector, implies that there is mutual trust and great commitment of all the stakeholders.

In this context, the main objectives of the Portuguese Mineral Resources cluster are:

- produce knowledge and induce innovation;
- enhance value creation and internationalization;
- promote efficiency in the use of resources;
- empower the stakeholders of the cluster;
- strengthen synergies between complementary activity sectors.

4.2. Portuguese Research and Development Projects **and the Portuguese Natural Stone Sector**

In this section, some of the most relevant Portuguese mobilizing research and development projects will be addressed.

4.2.1. The JetStone Project

The JetStone Project was created based on the collaboration between ten entities in the business, science and technology system. This project took place between 2005 and 2008 with the aim of increasing production flexibility and reducing the response time to market demands. According to the Technological Diagnosis of the Natural Stone Sector and Intervention Areas made by CEVALOR, in 2010 (Cabral De Melo et al., 2017), with the implementation of this mobilizing project, it was possible to:

- develop new and improved solutions for automatic cutting;
- differentiate and improve the product quality by using laser technology, which allowed the creation of non-slip marble and granite floors;
- develop an automatic raw material stock control system integrating a virtual simulation of the capacities of the company's existing cutting machines, which consequently guaranteed the optimization of raw materials and final product quality.

The design and creation of nine lean prototypes and six test and quality control devices, all validated in a production environment and currently used by several dozen manufacturers, was the project's most noticeable outcome (Antunes Da Silva, 2014).

With the aid of the technologies created as part of the Jetstone Mobilizer Project, ornamental stone businesses can now transform raw materials in a flexible manner and achieve noticeable reductions in raw material waste, which leads to productivity gains and increased responsiveness to microorders in the domestic and/or European market (Silva et al., 2020).

4.2.2. The InovStone Project

The Inovstone Consortium was responsible for the second wave of digital technology advancements for Portuguese Ornamental Rocks. Nineteen businesses and organizations from the scientific and technological system participated in a more extensive mobilizing collaboration that presented the Inovstone Mobilizing Project (Antunes Da Silva, 2014).

This research and development initiative, which was created to carry on the leanstone ideology's implementation after the foundation of Cluster VALORPEDRA, has a useful life between 2010 and 2013. It featured a collaboration of 15 entities, including natural stone enterprises, equipment firms, associations, and entities of the Scientific and Technological System, and produced eight solutions (PPS) and fourteen prototypes.

The goal of this initiative was to develop PPS-level innovations—Product, Process, and Service—to give the Natural Stone cluster's member companies the tools they need to innovate in these three areas. The following principles served as the project's foundation:

- increased involvement of a larger group of the natural stone cluster’s companies and entities;
- attract critical mass to the sector, thus increasing the value of the entire chain;
- seek the development of novel, contemporary, and distinctive manufacturing techniques that might add value and improve the standard and competitiveness of businesses in the industry;
- encourage the expansion of the cluster's exports either through product improvements in terms of pricing and technology or through a shift in mindset and attitude based on the businesses that have achieved notable levels of success by implementing the aforementioned approach.

The execution of such driving Research and Development (R&D) programs, like the JetStone and InovStone projects, has significantly influenced the growth of the competitiveness of the stone industry in Portugal (Frazão, 2016).

The use of the technologies developed under the InovStone project enables one to respond to medium-sized commercial opportunities in a flexible and competitive manner on global markets, as well as to significantly reduce raw material and energy waste, according to a number of recent studies conducted by authors from various Universities. The same research suggest that ornamental stone enterprises have been given a substantial push by the InovStone technology to transform their operations into Industry 4.0 (Silva et al., 2020).

4.2.3. The FlexStone Project

The FlexStone Research and Development Project, which ran from 2010 to 2013, produced the third generation of digital technology advancements for the natural stone technology. This FlexStone Project, supported on the leanstone concept, produced two innovative, cutting-edge prototypes. The following short-term goals were attained through the execution of this project (Cabral De Melo et al., 2017).

- ensure continuity in established markets with room for expansion;
- introduction new markets;
- increase product innovation and differentiation to better serve markets that are more demanding;
- continue the companies' technological development and integration;
- promote the Portuguese Natural Stone - Stone.PT brand and the sector's and companies' communication strategies;
- meet the demands of demanding markets (the primary markets for Portuguese natural stone), invest in product certification and long-term guarantees of the same.

The advancements made as part of this consortium project have led to technologies that allow businesses in the ornamental stone sector to respond to customized projects of any scale optimally and in an integrated manner, with a further reduction in waste of raw materials, energy, and ecological footprint, as well as a guarantee of a significant increase in productivity. This project has produced technology advancements that permit ornamental stone enterprises to bridge the gap between their operations and Industry 4.0 (Silva et al., 2020).

4.2.4. InovStone 4.0 and BIM technologies

The fourth wave of technological developments in Industry 4.0 for ornamental stone was portrayed by the Inovstone4.0 Mobilizer Project (InovStone 4.0 Project - Advanced Technologies and Software for Natural Stone, 2022). Seven institutions from the Research and Innovation Systems (universities and others) and 17 companies have been involved in the development and implementation of the InovStone 4.0 Project. They provide a crucial role in ensuring the application of science, fostering interactions between universities and businesses, and, most importantly, ensuring the sector's ongoing evolution. In the framework of BIM procurement in the construction industry, it seeks to promote InovStone 4.0 Collaborative Production (Antunes Da Silva et al., 2016).

BIM is a type of software that enables the representation of a building's physical and inherent characteristics as a guided model using objects connected to a database. This innovative approach to building design is altering the construction sector and will shift procurement, or how we buy, toward standardized goods. Portugal's ornamental stone industry places a strong emphasis on product personalization, which gives it a competitive advantage. This highlights the significance of the InovStone 4.0 mobilizer project, which will establish the necessary conditions through its collaborative network for the ornamental stones to give competitive advantages with the BIM implementation mandate (da Silva, 2018).

This creative dynamism in the decorative stone cluster is best demonstrated by the InovStone 4.0 mobilizer project. The approach that economically stimulates knowledge, turns concepts into products, fosters innovation, and increases industry and company competitiveness is the promotion of technical progress. Portugal needs such technological progress that stimulates economic expansion to compete in markets like Germany, France, and England, we must develop new products' technologies, manufacture them, and promote them through strong brands.

It is already clear from the industrial environment tests being conducted in these businesses that the prototypes will perform better than anticipated and that ornamental stone businesses can advance towards collaborative manufacturing and smart manufacturing by using these ground-breaking technological solutions. InovStone 4.0 technologies are designed to enable customers and suppliers to collaborate in a growing, personalized, and optimized co-creational approach to commercial opportunities of any scale. This is especially true with Building Information Modelling (BIM) users (Silva et al., 2020).

4.3. Benefits and sustainability in the stone industry

Companies today are moving beyond traditional industry silos and fusing into network ecosystems, creating new potential for innovation for many existing organizations as well as new problems. This one of the key motivations that mobilize the Portuguese ornamental stone industry to reduce waste and increase flexibility began with the first wave of technological development projects back in 2004.

In this context, the following research question may arise: What is the impact of R&D Mobilizing Projects on the sustainability, efficiency and image of Portuguese ornamental stone businesses? In response, it should be noted that ornamental stones are naturally available, non-renewable resources that must be used and handled in an efficient manner in order to reduce waste output and increase profitability. Considering the global average for the extraction of ornamental stones, only a third of the raw stone material that was harvested makes it to the market as a finished good. The other two thirds are waste. For any plan of competitive economic growth in nations aiming for sustainable development, the proper valuation of ornamental stones is key.

Due to this and the fact that ornamental stones are non-renewable natural resources, they must be extracted and handled properly for both economic and environmental reasons (Carvalho et al., 2018b).

Portugal's stone industry depends on its companies' capacity to provide value in the global marketplace. Portugal, while being a relatively small country, has a vast variety and quantity of stone to sell to the global market. Stone is an easily exportable product (Frazão, 2016).

The Portuguese stone industry has chosen a framework that aims to improve sustainable consumption and production patterns through sustainable management and efficient use of natural resources. This program, which takes the shape of R&D mobilization initiatives in business consortiums, sought goals and challenges to go forward in all directions and produce powerful firms that are more environmentally, socially, and economically sustainable (da Silva & Almeida, 2020)

The extraction and optimized transformation of ornamental stones using new machine tools have a clear impact on competitiveness, with improved energy efficiency, less waste, less water consumption, and faster operation times. As a result, new and improved products and processes can be developed, taking better advantage of the resource's natural attributes, and introducing modern and sustainable technologies (Carvalho et al., 2018b).

It is accepted that Portugal has a history with stone and a considerable variety of rocks that can be used as ornaments. The country's history is preserved in stone and by stone and can be found by simply traveling through the area that is now known as Portugal (Antunes Da Silva, 2014).

Portugal possesses a sizable and diverse stock of stones that are appropriate for aesthetic purposes, despite its modest area (Siegesmund & Snethlage, 2011).

There are two categories of marketable products: stone sold raw, and stone sold processed. The industrial process is typically divided into four phases: extraction, transportation, transformation, and marketing. According to the established commercial language, there are four different types of rock that have been discovered in Portugal and used for decorative purposes: marbles, limestones, granites, and schists (Antunes Da Silva, 2014). Once extracted, the various stone types provide a diversified range of goods depending on the various transformation processes, which are then distributed to the widest range of markets (Galetakis & Soultana, 2016).

One of the world's top manufacturers of ornamental stones, Portugal has had an average yearly increase in tons of 4% over the past 50 years (Carvalho et al., 2018b). According to information made available by the National Association of Extractive and Manufacturing Industry (ASSIMAGRA - Associação Portuguesa dos Industriais de Mármores, 2021), Portugal's sector is distinguished by the extreme importance it presents in its economy, giving rise to 2,112 businesses that employ 13,380 people nationwide and had a turnover of around 872 million euros in 2018.

The most prevalent technologies in this industry are some of the most cutting-edge in the world, used by Portuguese processing companies : (A) Stone Jet, an advancement in technology tested in the tanning industry, which enables the plate classification and defect detection through appropriate equipment, software, and an operator who makes the arrest and digitalization of the raw material's flaws prior to the cutting process; (b) Stone Cut, which utilizes the same technological features but in a more straightforward manner, permits an increase in production and straight cuts; (c) Computer Numerical Control (CNC), which enables digitalized numerical control of five axes, permits the modeling of parts in multiple forms, enabling the creation and implementation in 3D projects; Last but not least, (d), the Stone Cut Mille, is a device that combines various features, including scanning, sorting, finishing, cutting, and modeling. All the above mentioned are key technologies that successfully integrate the current Industry 4.0 concept.

5. Summary and Conclusion

This investigation into the Portuguese ornamental stone market serves as an excellent case study on the significance of industry digitalization. To turn the ornamental stone business from a rigid, traditional industry into a flexible, collaborative, and digitalized industry for the future of society, a strategic set of research and development initiatives were conducted in the Portuguese ornamental stone sector and are now being conducted at an industrial level.

These R&D initiatives cover the whole stone industry value chain, providing a comprehensive understanding of all processes, including marketing, extraction, design, preparation, planning, production, finishing, and dry layout of stone products.

Such digital transformation is crucial because it directly addresses the Triple Bottom Line principle and affects all environmental, social, and economic elements. As a result, the health and wellbeing of the stone industry's stakeholders is effectively maintained. Also, as shown, ornamental stone natural resources are used more effectively. Finally, improving business outputs has positive consequences on the economy and on people's well-being.

This shows that the Industry 4.0 concept not only addresses technological improvements and industry principles, but also approaches holistically dedicated sectors, such as the ornamental stone cluster to improve the efficiency and outputs through all of its value-chain.

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4. DIGITAL TWINS AND THE ORNAMENTAL STONE INDUSTRY: KEY FACTORS

The second article of this project deepens the discussion about the implementation of Industry 4.0 technologies, with a specific focus on the Digital Twins. This approach is of paramount importance since Digital Twins represent one of the most promising innovations in the modeling and simulation of physical systems. The main contribution of this study to the academic literature lies in the identification and analysis of key factors that influence the effectiveness of these technologies in the ornamental stone sector [4].

This chapter addresses a significant gap since previous studies have often focused on more conventional sectors. Through the rigorous application of a methodology that evaluates the impact of these technologies on operational efficiency, resource optimization and environmental sustainability, this work not only deepens the theoretical understanding, but also has significant practical implications [7].

Digital Twins, as virtual replicas of physical systems, have the potential to revolutionize real industrial applications, such as that of an ornamental stone manufacturing company. Implementing these technologies can result in significant time and money savings during prototype design and provide continuous diagnostics and optimization throughout a machine’s production. It is essential to recognize that although Digital Twins offer cost savings when considering physical processes holistically, their implementation should be done with caution, given the existence of several problematic issues still unresolved [1], [5].

The importance of incorporating additional software tools to improve the Digital Twins and the relevance of comparing the results of the virtual model with the real ones. It is concluded that the technology of Digital Twins will have a significant impact on business value, being beneficial to use this technology, despite the need for caution during the design phase [5], [10].

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DIGITAL TWINS AND THE ORNAMENTAL STONE INDUSTRY: KEY FACTORS

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Summary: *This paper discusses the application of Digital Twins (DTs), which are virtual replicas of physical systems, to a real-world industrial application of an ornamental stone manufacturing company. Implementing DTs can save time and money during prototype design and provide continuous diagnostics and optimization throughout a machine's production run. In addition, DTs are beneficial for cost savings because they consider physical processes holistically. In addition, the article emphasizes that the implementation of a DT must be done with care and that there are still numerous problematic issues to be resolved. The article also discusses the incorporation of additional software tools to enhance DTs and the significance of comparing the virtual model's results to the actual ones. The article concludes that Digital Twins technology will have a significant impact on business value and that it is beneficial to use this technology despite the need for caution during the design phase.*

Key words: *Digital Twins, Industry 4.0, Simulation, Applications, Ornamental Stone Sector.*

1. INTRODUCTION

Digitalization and automation have become increasingly essential to the market as the demand for industrial production efficiency has risen. This has required the development of more realistic and reliable simulation tools. In comparison to hardware models, digital models offer greater flexibility regarding use cases and lower resource requirements (Rosen et al., 2015; Tao et al., 2019). To standardize the creation of digital twins and reduce production costs, the Association of German Engineers (VDI) and the Association for Electrical, Electronic and Information Technologies (VDE) have published a guideline on virtual commissioning (Janda et al., 2019).

Digital Twin (DT) technology is one of the most prevalent areas of Industry 4.0, with the goal of achieving total virtualization through digitization. DT involves incorporating data in both directions between a physical and virtual machine. A DT is a virtual model of a real-world physical system that simulates its behaviour and monitors operations using real-time data sent by sensors on that system (Tao et al., 2019). When applying DTs to prototyping, engineers can validate the efficacy of industrial concepts without the need for prototypes by simulating the whole device. Early detection and correction of design flaws significantly reduces the cost of rectifying them during operation(Rosen et al., 2015).

In complex industrial processes such as manufacturing and production, simulations are essential to optimize processes. Hence, DT technology can increase manufacturing process efficiency and generate cost-effective consumer products. DT technology is also essential in engineering education to maintain curricula and education content and to provide students, instructors, and businesses with dedicated and efficient DT tools (Schuster et al., 2016; Tao et al., 2019).

CAx software has grown to be an integral component of any design office that applies complex simulations. They can be used for calculations (CAE), design (CAD), and simulation of manufacturing (CAM). These programs include Inventor, Solid Edge, Solid Works, and NX. Through the Mechatronics Concept Design (MCD) application, the NX program provides tools for interactively simulating the complex motion of a mechatronic system (Fait et al., 2022). The MCD application consists of several subcomponents, including system engineering, mechanical concept, simulation, mechanical, electrical, automation, and design collaboration (Holzer et al., 2022).

The use of DTs in the industry allows companies to improve production efficiency, reduce costs, and increase product quality. With accurate, real-time simulation, flaws can be detected and corrected even before production, thus avoiding waste, and lost time. In addition, DT technology can be used to maintain optimized production operations and increase the efficiency of the manufacturing process (Tao et al., 2019; Yang et al., 2017).

In conclusion, DT technology represents a significant step forward for industry and engineering education. With increasingly accurate and realistic simulation tools, valuable results are generated that can be efficiently used in real-world applications (Fait et al., 2022; Janda et al., 2019). Notably, in addition to its benefits for production efficiency, DT technology can also bring about significant sustainability advancements. By simulating production processes in their entirety, it is possible to identify areas for enhancement to reduce the waste of energy, materials, and natural resources and to minimize the production's environmental impact. This can assist businesses in meeting rising demands for more sustainable and accountable production (Liao et al., 2017a; Tao et al., 2019).

When broken down into well-defined stages, implementing a DT in a dedicated industry can be carried out efficiently and effectively. Figure 1 illustrates the process of developing and deploying a DT in the Ornamental Stone Sector, from data acquisition to results analysis. Understanding these stages is crucial for the effective deployment of a DT to such a real-world application.

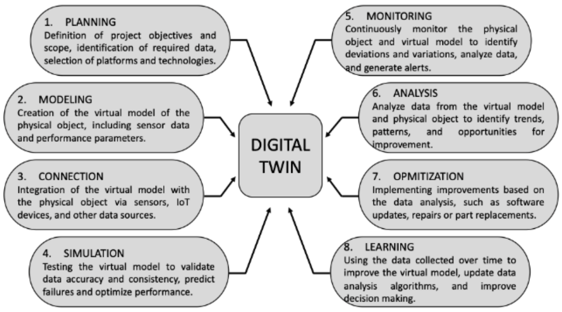

Figure 1: Main steps to create and implement a Digital Twin in the Ornamental Stone Sector.

2. LITERATURE REVIEW

Industry 4.0 is one of the driving forces behind the development of DT technology. The implementation of the DT methodology is regarded as a crucial element for the transformation of manufacturing and, consequently, the industry's future. DTs allow for the optimization of the product development process, the reduction of costs, the acceleration of time to market, and even the prediction and avoidance of potential production problems (Janda et al., 2019; Tao et al., 2019).

One of the best-known tools for creating DTs is Mechatronics Concept Designer (MCD), a subsystem of Siemens' PLM software system and a platform on NX developed to address mechatronic product design and automatic motion simulation issues. It comprises of two systems: the physical system and a virtual system that contains all the information about the physical system. (Tao et al., 2019), (Tao et al., 2022).

Maslow's pyramid is a psychological theory that depicts five levels of human needs, from physiological to self-actualization (Maslow, n.d.). This pyramid is used in Industry 4.0 to represent the hierarchy of cyber-physical systems, from sensors to management software, that facilitate automation of production processes and data-driven decision making (Ryan & Deci, 1985). Figure 2 depicts the application of Maslow's hierarchy of needs to the ornamental stone industry, specifically a CNC milling machine for the production of stone slabs.

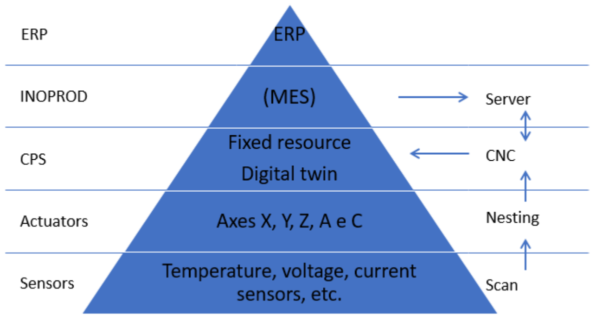

Figure 2: Maslow's pyramid applied to Industry 4.0: hierarchy of cyber-physical sustems and the role of management software.

The sensors at the base of the pyramid collect data from the physical environment, such as temperature, pressure, and vibration, and send it to the cyber-physical system. The second level of the pyramid, the actuators, receives this data and then acts on the physical environment, conducting tasks such as moving machinery and activating control systems (Lee et al., 2015; Liao et al., 2017a).

The cyber-physical system occupies the third level of the pyramid and is responsible for processing and analyzing the data received from the sensors and actuators and making decisions based on this information. This layer consists of a network of devices, including computers, sensors, and actuators, that collaborate to automate production processes (Liao et al., 2017a).

In the context of Industry 4.0, the Manufacturing Execution System (MES) is an instrument belonging to the fourth level of Maslow's hierarchy of needs. This tool is essential for the automation of production, as it permits the accumulation and analysis of production process data in real time, resulting in enhanced efficiency, productivity, and product quality. The use of MES is directly related to the DT concept, which involves the creation of a digital replica of a product, process, or system to enable simulations and virtual optimizations prior to actual implementation (Rosen et al., 2015; Tao et al., 2019).

At the apex of the pyramid is the ERP (Enterprise Resource Planning) management software, which utilizes the collected data to optimize production processes and make strategic decisions. This software is responsible for integrating the various company departments, including production, sales, finance, and logistics, and provides the management team with an integrated view of the company's production processes and performance indicators (Liao et al., 2017a; Rosen et al., 2015).

In this way, Maslow's pyramid is a useful analogy for conceptualizing the hierarchy of cyber-physical systems in Industry 4.0 and how the integration of these systems can lead to increased production efficiency, higher quality, and reduced costs (Liao et al., 2017a).

2.1. Digital Twin Technology Applications

DT technology has numerous applications across numerous industries. In the manufacturing industry, it can be used for product design, simulation, and optimization, making it one of its primary applications. DTs can be used to create a virtual model of a product or process, which can be used to simulate various scenarios and optimize the design and production processes. This can result in substantial cost reductions and a shorter time to market (Liao et al., 2017a; Tao et al., 2019).

This technology also has applications in the field of maintenance and repair. By using DTs to monitor equipment performance and forecast potential failures, maintenance can be performed proactively, thereby reducing downtime and boosting productivity. It has been demonstrated that predictive maintenance is more effective and less expensive than traditional reactive maintenance (Liao et al., 2017a; Tsai et al., 2020).

DT technology has extensive and diverse applications, and its implementation has the potential to revolutionize numerous industries. Future applications of digital siblings are likely to become even more inventive as technology continues to advance (Tao et al., 2019).

3. METHODOLOGY

This paper explores the capabilities of automation in solving real-world problems by employing digital tools and DT technology. Using a virtual model created with Siemens NX Mechatronic Concept Designer (MCD) and Simit, the objective is to provide practical and comprehensive applied examples.

This strategy intends not only to improve problem comprehension, but also to increase efficiency and accountability in their resolution.

The kinematic model is derived from simplified 3D models for simulation purposes. Individual rigid bodies are defined and then connected via joints, allowing the virtual machine to replicate the movements of a physical machine. This is crucial because it ensures that the simulation is as accurate as feasible.

In this case-study, the MCD software serves as a tool for the mechatronic part of the machine, allowing the definition of the 3D model and all of its movements, in addition to sensors, physical characteristics, and input/output signals. This allows for extremely precise control over the virtual machine's behaviour.

The first step in creating a DT is to define the physical and mechanical characteristics of the machine's various components. The Mechatronic Concept Designer enables you to simulate the dynamic behaviour and interactions of the various parts by allowing you to add rigid body and collision body properties, as well as designate the movement possibilities of their connections (sliding joint, ball joint, etc.). This enables the simulation to be extremely accurate and realistic.

MCD is a commercial application within Siemens NX software that facilitates physics-based simulation and is utilized in virtual commissioning and the creation of digital twins. The advantage is the close proximity to the Siemens NX CAD tool, which makes the software simple to use. The reuse library enables validation of the designed product by allowing the user to rapidly add data to the functional model, such as joints, motion, sensors, crash behaviour, and other kinematic and dynamic properties for each component (Fait et al., 2022).

In addition to enabling the definition of signals and signal adapters, the MCD software allows for the development of event-based machine behaviour governed by virtual sensors. Position function control is used to define the speed, acceleration, force, etc., at which the part can move within its defined position based on the connections. This allows the simulation to be extremely accurate and effective in solving real-world issues (Holzer et al., 2022).

4. DISCUSSION

Prior to contemplating the use of a dedicated DT in a production system of the Ornamental Stone Sector, several steps and factors must be taken into account beforehand.

The main goal of this applied DT is to reflect reality as accurately as possible of the corresponding manufacturing system of the ornamental stone industry. Due to the complex dynamics involved, however, some features are extremely difficult to replicate. Future optimization relies heavily on the successful design of a digital counterpart. Real-world mechanical and electronic issues can be studied and verified in a safe, regulated environment. These research findings can be used to predict and prevent prospective system problems before they occur.

In this ornamental stone device, as for other industrial applications, older mechanical applications are frequently replaced by servo drives and intelligent motion control, thereby enhancing the system's dynamic and power characteristics. Additionally, mechatronic systems tend to be more flexible and endure less wear and strain.

The MCD does not simulate sensors in reality; rather, it replicates their functionality. It does not address their physical characteristics. Real sensors can get unstable in certain environments (due to magnetism, rapid motion, etc). As also observed by Jaya (Institute of Electrical and Electronics Engineers Malaysia Section et al., n.d.), this can result in unanticipated errors during prototype development, highlighting the need to test and optimize a system prior to implementation.

When considering the use of STEP files, these can be imported into the NX mechatronics concept designer, but they are converted into "Siemens part files," an internal Siemens data format, which imposes import restrictions. In addition, MCD permits mesh-by-mesh collision, with the limitation that each mesh may contain no more than 1024 vertices. MCD can therefore only exhibit original meshes with a maximum of 1024 vertices. In addition, the vertices are always distributed uniformly throughout the body and cannot be locally concentrated to obtain a more accurate representation of collision-heavy regions. Future projects must consider software and hardware constraints and adjust simulation models accordingly.

In our DT applied to the specialized ornamental stone system, the MCD enables OPC signal mapping with the PLC and other applications. This mapping enables the OPC server and simulation object to communicate. This means that simulation objects can be controlled by a (virtual) PLC and simulation processes can function as control process parameters. Future concepts include attempting to communicate with a real PLC and programming a rudimentary control using the JOINT coordinate system. It is imperative to remember that the simulation environment must be meticulously calibrated and tested in order to produce accurate results.

In addition, incorporating this DT into our system can result in improved decision-making, cost and labour savings, and an increase in system efficiency. The use of this type of DT can also lead to a reduction in environmental impact, as it permits the early identification and resolution of problems that may result in the waste of natural resources.

Nevertheless, it is key to remember, that a digital counterpart can never be an exact representation of the actual system. As mentioned by *Liao et al.* (Liao et al., 2017b) there are actual limitations related to the available hardware and software, as well as the accuracy of the employed models that affect the sensing operating environment of the actual system which may differ significantly from the simulation environment, thus leading to some degree of inaccuracy in the measured results.

Therefore, it must be considered that such applied DTs must be meticulously designed and validated to ensure their reliability and accuracy. Also, it is key to enhance that our DTs must be continuously updated and improved to reflect system changes.

In a nutshell, it can be highlighted that the implementation of a dedicated DT to an applied system of the ornamental stone industry allows for improving the design, testing, and operation of existing solutions, resulting, therefore, in more efficient, safer, and sustainable systems.

5. CONCLUSION

Digital twin technology could seem to be an overly complex simulation, but if applied properly, it can save a significant amount of time and money when designing prototypes. Continuous diagnostics and optimization throughout a machine's entire production time will be a game-changing factor.

The successful design of a digital twin will be crucial for future optimization, as the complexity, quality, and adaptability of the complete production or individual products will continue to increase. Therefore, digital twins should be structured with as much design and production flexibility as possible.

DTs can provide real-time data on the condition and status of physical assets through continuous learning. Management will be able to monitor systems, develop more precise plans, and forecast, for instance, the time required to service critical components.

DTs are particularly useful for saving costs because they allow for a holistic view of physical processes, which will be particularly true in situations where large amounts of data will be required. However, it will be necessary to approach the design phase very carefully because there will still be many problematic aspects to consider beforehand to the simulation of the system.

When considering the implementation of a dedicated DT to an industrial-level application due to the need to analyse and characterize complex real-world interactions in a simplified approach. However, and as referred by Tao *et al.* (Janda et al., 2019; Tao et al., 2019), even though it may be very difficult to predict and simulate real-world complexity, it will still be worthwhile to use this technology.

For the case of MCD, there is a great potential for DT improvement and functionality enhancement. The integration of other software packages will enable to include hydraulics, heat transfer and other effects to the digital model. These increased functionalities may belong to a second age of DT and its validation will require to compare the digital results to the results obtained on the ornamental stone system.

For communication between different programs and devices, the OPC server will be a good solution. Also, the use of the mechatronics module will make it possible to use the robot to perform the simulation using a pre-programmed motion sequence (in PLC program). The XML data exchange method will be applied between MCD and other PLM subsystems, which will help integrate the data of MCD and other subsystems, to enhance the advantages of information exchange, provide the implementation method of continuous connection in relevant systems, and enhance the core competitiveness of products. Hence, as mentioned by Lysek *et al.* (Konstantinov et al., 2017; Lysek et al., 2019) it will be the basis of collaborative design in MCD, which will not only be suitable for Siemens PLM systems, but also for other similar software systems or Internet development engineering.

In general, DT technologies offer significant opportunities for increasing the efficacy and precision of design and production processes. Although there are still some additional obstacles to overcome, such as the need to incorporate additional numerical models and the complexity of the physical world's interactions. In addition, the integration of other software tools and communication between programs and devices can contribute to the enhancement of the efficacy of DTs.

The DT technology will likely play an ever-increasing role in the future of the industry, and businesses that adopt and implement this technology will enjoy a substantial competitive advantage. Adoption of this technology has a high potential for cost reduction and enhancement of product's commercial value, making it a prospective strategy for companies in a variety of industrial sectors, particularly the Ornamental Stone Industry.

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5. DESIGN AND IMPLEMENTING OF A DIGITAL TWIN FOR A STONE-CUTTING MACHINE: A CASE STUDY

The third article of this project continues to explore the evolution of Industry 4.0 and the implementation of Digital Twins in the ornamental stone industry. As research progresses, it becomes crucial to address the technical and practical challenges associated with implementing these emerging technologies. In this context, the article focuses on a topic of critical relevance: the comparative analysis of connection options for the implementation of a Digital Twin in a stone cutting machine [4].

The ornamental stone industry, with its peculiarities and specific challenges, requires solutions that not only incorporate technological innovations, but are also viable from an operational and financial point of view. The appropriate choice of connection options is critical to ensure the effectiveness of the implementation, considering aspects such as communication speed, security, scalability, and costs. An inadequate choice can compromise the integrity of the system, resulting in operational inefficiencies and potential risks [11].

This chapter deepens the comparative analysis of these connection options, considering technical and operational variables. The approach adopted is rigorous and focused on solutions, to identify the most suitable option for the implementation of Digital Twins in stone cutting machines. The study explores two main options: the first involves the use of Industrial Internet of Things (IIoT) devices and an Message Queuing Telemetry Transport (MQTT) broker to enable real-time data exchange; the second option employs conventional automation devices and a Virtual Private Network (VPN) connection to ensure data security during transmission [5], [11].

Both options are evaluated based on criteria such as communication speed, security, scalability, ease of implementation, cost, complexity, and technical requirements. The results of this comparative analysis provide valuable insights into the Digital Twin implementation of the stone cutting machine, allowing the selection of the most suitable option based on these considerations [5].

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5th International Conference on Industry 4.0 and Smart Manufacturing

DESIGN AND IMPLEMENTING OF A DIGITAL TWIN FOR A STONE-CUTTING MACHINE: A CASE STUDY

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Abstract

The use of digital twins in the development and management of stone-cutting devices presents real challenges in the field of industrial stone manufacturing. Digital twins help manufacturers achieve increased precision, efficiency, and cost-effectiveness, ultimately transforming the landscape of stone manufacturing operations. Such digital twins enable real-time monitoring, predictive maintenance, and virtual simulations. This paper explores two options for connecting a physical stone-cutting machine in a company to its digital twin. The first option involves using Industrial Internet of Things (IIoT) devices and a Message Queuing Telemetry Transport (MQTT) broker to enable real-time data exchange. This approach provides agile and efficient communication between the physical machine and its digital twin. The second option employs conventional automation devices and a VPN connection to ensure data security during transmission. The two options were evaluated by considering criteria such as communication speed, security, scalability, ease of implementation, cost, complexity, and technical requirements. The results of the comparative analysis provide valuable insights for the implementation of the digital twin of the stone-cutting machine, allowing the selection of the most suitable option based on these considerations.

Peer-review under responsibility of the scientific committee of the 5th International Conference on Industry 4.0 and Smart Manufacturing

Keywords: Digital Twin, IIot, Security and Real-Time Data Exchange.

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1. Introduction

The concept of a digital twin has gained prominence in the industry as an innovative approach to improving efficiency, optimizing processes, and improving decision-making. A digital twin is a virtual representation of a physical object, process, or system that replicates the characteristics, behaviors, and real-time interactions of its real-life counterpart [1].

The relevance of the digital twin lies in its ability to provide a comprehensive and accurate view of an asset or system, enabling advanced simulations, monitoring, and analysis. Through the combination of sensors, real-time data collection, and virtual models, the digital twin enables a deep understanding of the performance, maintenance, efficiency, and behavior of the corresponding physical object. In industry, the use of digital twins has shown promise in several sectors, including manufacturing, energy, transportation, and infrastructure. With a digital twin, companies can simulate different scenarios, conduct virtual tests, optimize processes, and make decisions based on real-time data. This results in reduced costs, increased operational efficiency, minimized risks, and improved quality of products and services [2].

In the context of stone-cutting machines, a digital twin offers the opportunity to monitor performance in real-time, predict failures, optimize the cutting process, perform virtual simulations, and test alternative configurations. In addition, it enables collaboration and remote access, providing a detailed view of the machine's status and operation for specialists and teams in different locations [2], [3].

When considering the relevance of digital twins in the industry and the potential benefit to the stone-cutting machine, it is essential to evaluate the connection options between the company and the Polytechnic Institute of Leiria (IPL) to ensure efficiency, security, and real-time communication [4].

In this article, the object of study for the digital twin is the StoneCUT LINE stone cutting machine, manufactured by CEI-Zippor. StoneCUT LINE is an advanced and specialized machine widely used in the stone and marble processing industry. The StoneCUT LINE is a high-precision stone cutting machine designed to automate the process of cutting, polishing, and finishing stone materials. It is equipped with a variety of advanced tools and technologies to deliver precise cuts, operational efficiency, and superior quality [5].

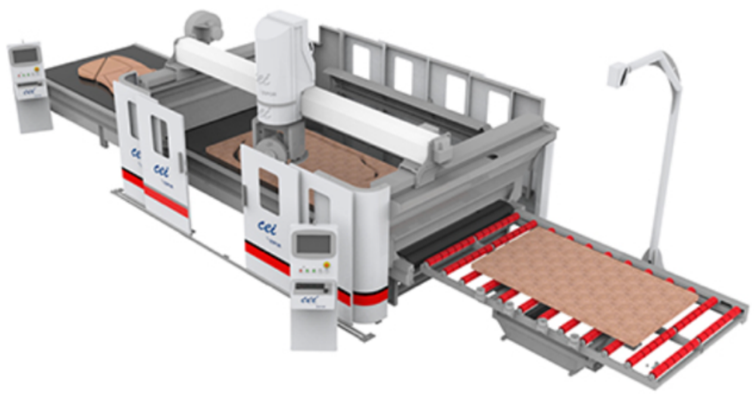

Fig. 1: StoneCUT® LINE [5].

The machine incorporates features such as laser positioning systems, robotic arms, or CNC (Computer Numerical Control) devices, laser measurement systems for detecting and correcting stone irregularities, and sensors to monitor and control key parameters during the cutting process [5].

The implementation of a digital twin for the StoneCUT LINE stone cutting machine presents several advantages and opportunities. By creating an accurate, real-time virtual model of the machine, it is possible to perform simulations, analyses, and optimizations before even performing operations on the physical machine [2].

Using the digital twin, you can continuously monitor the performance of the StoneCUT LINE, collect real-time data from sensors and compare this data with the virtual model to identify potential faults, adjustments, and improvements. In addition, you can perform simulations of different cutting conditions, test new cutting programs and strategies, and optimize the workflow, resulting in increased efficiency and productivity [2], [3].

Collaboration between the company and the Portuguese Leiria Polytechnic (IPL) Engineering School through a StoneCUT LINE's digital twin provides an advanced learning environment, allowing students and experts to remotely access the digital twin to study machine operation, test virtual settings, and develop new cutting programs [2].

Choosing the appropriate connection option between the enterprise and the IPL is essential to ensuring real-time data transfer and information security. Two options will be discussed below: connection by Industrial Internet of Things (IIoT) and Message Queuing Telemetry Transport (MQTT) broker devices, and connection by conventional automation devices and VPN [4], [6].

The objective of this paper is to perform a comparison between two connection options between the company, where the StoneCUT LINE stone cutting machine is located, and the IPL, where its digital twin will be deployed. The two options to be considered are:

- Connection by IIoT devices and MQTT broker: In this option, it is proposed to establish the connection between the company and the IPL by means of IIOT devices and to use an MQTT broker for data exchange. The IIoT devices are responsible for collecting real-time data from the physical machine and sending it to the MQTT broker, which acts as an intermediary to distribute the data to the digital twin on the IPL [7], [8].
- Connection via conventional automation devices and VPN: The second option involves connecting the company and the IPL via conventional automation devices, such as programmable controllers, and using a VPN (Virtual Private Network) to ensure the security and integrity of the transmitted data. The VPN creates an encrypted tunnel between the enterprise and the IPL, allowing the secure transfer of the digital twin data [1], [3].

Comparing these two connection options, several relevant criteria will be considered, such as communication speed, security, scalability, ease of implementation, and associated costs. The objective is to provide a comprehensive and informed analysis to assist in the selection of the best connection option between the enterprise and the IPL in the context of the digital twin of the StoneCUT LINE stone cutting machine [3].

Through this comparison, it is hoped that companies and educational institutions will learn how to set up efficient and secure connections for implementing industrial digital twins, taking into account the specifics of the stone-cutting machine and the communication needs between the real machine and the digital twin [1], [6].

2. Literature Review

The IIoT is a concept that refers to the interconnection of devices, machines, sensors, and industrial systems via the internet. It extends the concept of the Internet of Things (IoT) into the industrial environment, enabling the collection, exchange, and analysis of data in real time. The IIoT enables machines and industrial systems to communicate with each other and with IT systems, enabling process automation, production optimization, and data-driven decision making. This results in greater efficiency, reduced costs, and improved quality of industrial products and services. The IIoT plays a key role in the implementation of digital twins, providing the infrastructure needed for communication between the physical machine and the digital twin [1].

MQTT is a lightweight and efficient communication protocol designed for IoT and IIoT environments. It enables the exchange of messages between connected devices following the publish/subscribe model. MQTT is suitable for networks with limited resources, such as bandwidth and power, as it uses a minimal amount of data and has low overhead. In addition, MQTT supports asynchronous communication, ensuring reliable message delivery even in unstable network conditions. It is widely used to facilitate real-time information exchange between devices, applications, and systems in IoT and IIoT. Using an MQTT broker in the connection between the enterprise and the IPL can facilitate the transmission of data from the digital twin of the stone cutting machine [6].

Using IIoT devices in conjunction with connecting via MQTT broker brings several benefits and features that boost the efficiency and scalability of solutions in the industry. In the following, I will discuss some of these benefits and features [6], [9]:

- Real-time data collection: IIoT devices can collect real-time data from sensors and connected devices in the industry. This enables continuous monitoring of operations, rapid detection of faults or anomalies, and agile decision making based on up-to-date information [10].
- Connectivity and interoperability: IIoT devices are designed to easily connect to different industrial systems and protocols, enabling efficient integration with a variety of existing equipment and infrastructures. This interoperability facilitates the creation of a connected ecosystem, where devices can seamlessly exchange information [6].
- Resource efficiency and optimization: With real-time data collection and advanced analytics, IIoT device-based solutions can optimize the use of industrial resources such as energy, raw materials, and production time. For example, production parameters can be monitored and automatically adjusted to maximize energy efficiency or minimize waste [11].
- Scalability and flexibility: IIoT and MQTT broker device-based systems are highly scalable, meaning that you can easily add or remove devices without major infrastructure changes. In addition, they offer the flexibility to adapt to different business requirements and needs, allowing for the implementation of customized solutions and gradual expansion [6].
- Low latency and minimal overhead: The MQTT protocol is designed to be lightweight and efficient, resulting in low latency and minimal network overhead. This is particularly important in industrial environments, where fast responses and real-time communication are essential to ensure efficient and safe operations [11].
- Security: The MQTT broker can be configured with advanced security features such as authentication, authorization, and encryption, ensuring the confidentiality and integrity of the transmitted data. This is critical to protect sensitive information and prevent cyber-attacks [4].

Overall, the use of IIoT devices and connection via MQTT broker provide greater visibility, control and informed decision making in the industry. These solutions drive digital transformation, enabling the implementation of smarter, more efficient and connected processes that contribute to increased productivity and improved business results [3].

VPN is a widely used technology for establishing secure connections between networks. It allows data to be transmitted in encrypted form, ensuring confidentiality, authentication, and integrity of information [4], [12].

The main function of a VPN is to create a virtual "private network" over a public network, such as the Internet. It establishes an encrypted tunnel through which data is securely transmitted between the connection endpoints. This means that even though data is being transmitted over a public network, it remains protected against interception and unauthorized access. By using a VPN, the following benefits and features are achieved: security, privacy, secure remote access, inter-network connections, and centralized management. VPN provides an additional layer of security, protecting sensitive data from cyber threats. Data encryption ensures that only authorized recipients can access and understand the information transmitted. In addition, VPN ensures communication privacy by hiding data traffic from prying eyes, you can establish secure connections for remote access, allowing employees, partners, or remote users to securely access the corporate network. This enables remote work, secure collaboration, and access to restricted resources, such as servers and internal systems, as if they were physically connected to the local network [4].

VPN also facilitates secure connections between different networks, such as branch offices of a company, external vendors, or business partners. This enables secure communication and resource sharing between organizations without compromising data security. In addition, they offer centralized management capabilities, allowing organizations to efficiently configure and control VPN connections. This simplifies administration, monitoring, and implementation of security policies. VPN is a common and reliable technology for establishing secure connections between networks. It plays an important role in protecting data by ensuring the privacy, integrity, and authenticity of the information transmitted. When comparing connection options for the digital twin of the stone cutting machine, the use of a VPN can provide an additional layer of security for data transmission between the company and the IPL [4], [6].

3. Methodology

In this chapter, a detailed description of the link options available to connect the physical stone cutting machine in the company to its digital twin in the IPL will be presented. These options have been carefully analyzed taking into consideration factors such as communication speed, security, scalability, and ease of implementation.

Two distinct connection options will be presented: the first involves the use of IIoT (Internet of Industrial Things) devices and an MQTT broker for real-time data exchange, while the second option uses conventional automation devices and a VPN connection to ensure the security of the transmitted data. Both options have advantages and disadvantages, and they will be detailed below for a comprehensive understanding of the available solutions [4], [6].

The first connection option between the enterprise and the IPL for the digital twin of the stone cutting machine uses IIoT and MQTT broker devices, enabling real-time data exchange between the physical machine and the digital twin [10], [13], as shown in figure 2:

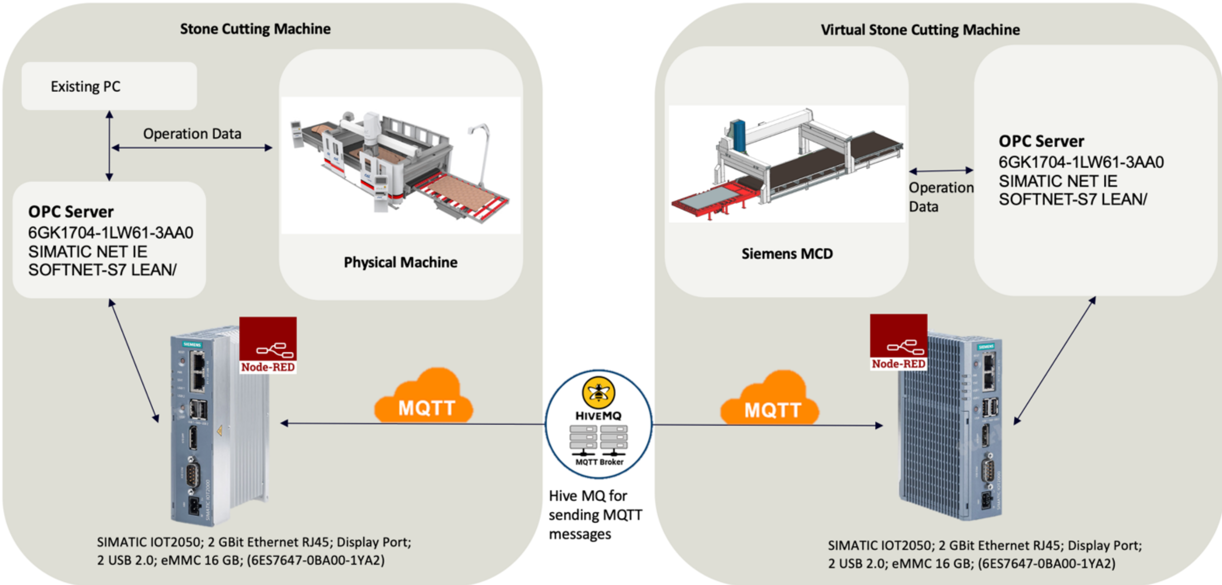

Fig. 2: Option 1 with IIoT devices and connection via MQTT broker.

In this scenario, the physical stone cutting machine is equipped with an internal PC that sends and receives operation data to an OPC Server called SIMATIC NET IE SOFTNET-S7 LEAN/6GK1704-1LW61-3AA0, this is an OPC server (OLE for Process Control) developed by Siemens to enable efficient communication between industrial automation devices and supervisory and control systems. It acts as an interface between the connected devices and the monitoring and control software, providing real-time data access and enabling the exchange of information in a reliable and secure way. SIMATIC NET IE SOFTNET-S7 LEAN/ offers advanced features such as support for industrial communication protocols, handling large volumes of data, and seamless integration with the automation environment [14], [15].

The data from the physical machine is then sent to a device called SIMATIC IOT2050; 2 GBit Ethernet RJ45; Display Port; 2 USB 2.0; eMMC 16 GB; 6ES7647-0BA00-1YA2, which is in the factory. The SIMATIC IOT2050 is an industrial computing device developed by Siemens to support Internet of Things (IoT) applications in the industrial environment, is equipped with advanced features such as high-speed connectivity through two GBit RJ45 Ethernet ports, enabling fast and reliable communication with other network devices. In addition, it has a Display Port for connection to external monitors, two USB 2.0 ports for connecting peripherals, and a 16 GB eMMC memory for data storage. SIMATIC IOT2050 provides a robust and scalable environment to run IoT applications, enabling real-time data collection, local processing, and connectivity to cloud systems for analysis and decision making. It is widely used in industry to enable digitization and process automation [12], [16].

Data transmission occurs via the MQTT protocol, which is a lightweight and efficient protocol for exchanging messages between Internet-connected devices. Node-RED, a visual programming environment [17], is used in SIMATIC IOT2050 to send and receive MQTT messages. These messages are transmitted in encrypted form, ensuring data security during communication [12], [16], [17].

To enable real-time data exchange, an MQTT broker, such as the Hive MQTT broker, is used as an intermediary to route messages between the SIMATIC IOT2050 in the factory and another SIMATIC IOT2050 in the IPL. The MQTT broker ensures that messages are delivered correctly and in real time, enabling efficient communication between the physical machine and the digital twin [12], [16], [17].

In IPL's SIMATIC IOT2050, MQTT messages are received and processed by the Node-RED. The data is then sent to the NX MCD software, which is responsible for running the digital twin of the stone-cutting machine. The digital twin is a virtual representation of the physical machine, allowing real-time simulation and monitoring of its operation [9], [16], [17].

This connection approach using IIoT devices and MQTT broker enables real-time data exchange between the physical stone cutting machine and the digital twin. This makes it possible to monitor, simulate, and analyze machine performance in a virtual environment, providing valuable insights for process optimization, fault detection, and continuous improvement. In addition, the use of MQTT ensures efficiency, security, and reliable communication between the devices, facilitating integration and information exchange between the company and the IPL [2], [9].

The second connection option between the company and the IPL for the digital twin of the stone cutting machine uses conventional automation devices and a VPN (Virtual Private Network) connection, providing security in data exchange [13], [18], according to figure 3.

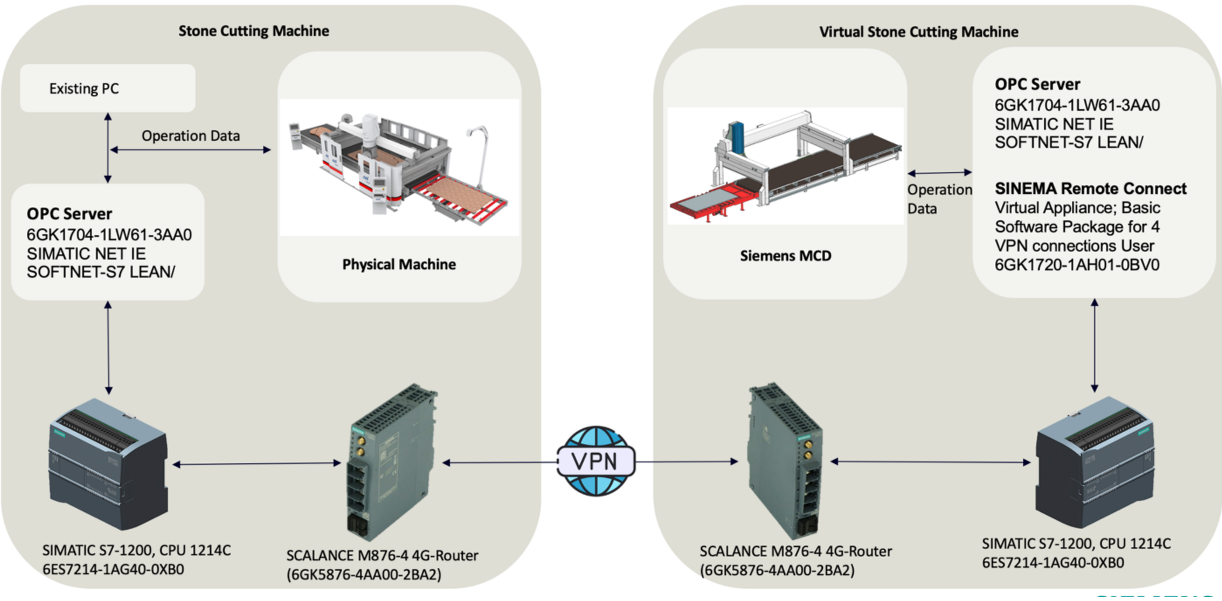

Fig. 3: Option 2 with conventional automation devices and VPN connection.

In this scenario, the physical stone cutting machine has an internal PC that sends and receives operation data to an OPC Server SIMATIC NET IE SOFTNET-S7 LEAN/6GK1704-1LW61-3AA0, the same as in option 1.

The data from the physical machine is forwarded to the SIMATIC S7-1200, CPU 1214C 6ES7214-1AG40-0XB0, which is a compact programmable controller (PLC) developed by Siemens. It is part of the SIMATIC S7 family and is designed for the automation of small and medium-sized industrial applications. The 1214C CPU, with model number 6ES7214-1AG40-0XB0, is a specific variant of the SIMATIC S7-1200 that offers specific features and capabilities. The controller has an integrated CPU that runs programs written in programming languages such as ladder diagram (LD) and structured text (ST). It has numerous digital and analog inputs and outputs for connection to sensors, actuators, and other automation devices. The SIMATIC S7-1200 is highly reliable and offers advanced features such as integrated communication via Ethernet and support for real-time communication with other devices. It is widely used in various industries for controlling and monitoring automated processes [3], [9], [19].

The SIMATIC S7-1200 in turn sends and receives data to the SCALANCE M876-4 4G-Router (6GK5876-4AA00-2BA2) in the enterprise. The SCALANCE M876-4 4G-Router is an industrial routing device developed by Siemens. It is designed to provide reliable and secure network connectivity in industrial environments. The router is equipped with 4G technology, enabling connection to high-speed mobile communication networks. It offers advanced routing features such as Network Address Translation (NAT) and integrated firewall to ensure data security and protect the network from external threats. In addition, the SCALANCE M876-4 is designed to operate in harsh conditions such as extreme temperatures, vibration, and electromagnetic interference, making it suitable for use in challenging industrial environments. The model number 6GK5876-4AA00-2BA2 refers to a specific variant of the device, which may have additional features or customized configurations depending on the user's needs. This Router has VPN capabilities that allow it to establish a secure connection with another SCALANCE M876-4 4G-Router in the IPL. Through this VPN connection, data is encrypted and securely transmitted between the routers [12], [20].

Upon arrival at the SCALANCE M876-4 4G-Router on the IPL, the data is forwarded to the SIMATIC S7-1200. This controller is responsible for receiving and sending the data to the Digital Twin of the stone cutting machine, which also uses the OPC Server SIMATIC NET IE SOFTNET-S7 LEAN/ [14].

To ensure security during data transmission, a VPN connection is used. The VPN establishes an encrypted tunnel between the devices in the company and the IPL, protecting data from interception and unauthorized access. This ensures that sensitive information related to machine operation and performance remains secure during data exchange [4], [21].

In addition to the VPN connection, the SINEMA Remote Connect Virtual Appliance with the basic software package for 4 VPN connections (6GK1720-1AH01-0BV0) is used. SINEMA Remote Connect Virtual is a virtualization application developed by Siemens. It is part of the SINEMA Remote Connect solution set, designed to facilitate secure remote access to industrial devices and networks. The application enables the creation of virtual machines (VMs) for running applications and operating systems in virtualized environments. It offers advanced features such as network isolation, data protection, and access security, ensuring that industrial devices and networks remain protected from cyber threats during remote access. SINEMA Remote Connect Virtual provides a flexible and reliable platform for implementing secure connections and managing devices and systems remotely in industry [4], [12], [22].

The use of conventional automation devices and a VPN connection provides an additional level of security for the communication between the physical stone cutting machine and the digital twin. The VPN connection ensures the integrity, confidentiality, and authenticity of the transmitted data by creating a virtual private network between the company and the IPL. This is particularly important when it comes to critical and confidential data that can be exploited if it is exposed to external threats [4].

In addition to safety, the use of conventional automation devices allows direct integration with existing controllers on the physical machine, facilitating the exchange of information and real-time monitoring. This provides a complete and accurate view of the machine's performance, enabling more detailed analysis and decision making based on reliable data [9].

A comparison between the two connection options, IIoT and MQTT Broker devices versus conventional automation and VPN devices, can be made based on relevant criteria such as communication speed, security, scalability, and ease of implementation [4], [6].

In terms of communication speed, the IIoT and MQTT Broker device option stands out. This approach enables a real-time exchange of data between the physical machine and the digital twin. Communication is fast and efficient, enabling an immediate response to changes in the stone-cutting machine [2], [9].

As for security, both options offer an adequate level of protection. In the case of IIoT and MQTT Broker devices, the data exchange is encrypted, ensuring confidentiality of information during transmission. In the option of conventional automation devices and VPN, the VPN connection establishes an encrypted channel that protects data against unauthorized access and interception [4], [12].

When it comes to scalability, the choice of IIoT and MQTT Broker devices is highly advantageous. IIoT devices can be easily added or removed from the network, while the MQTT Broker allows advanced message management and supports the connection of multiple devices. This enables flexible system expansion [10].

The choice of conventional and VPN automation devices is also scalable. The conventional automation infrastructure can be expanded to handle a larger number of devices, and VPN allows secure connection from different locations, enabling system expansion to new units or branches [4].

As for ease of implementation, both options have their peculiarities. The IIoT and MQTT Broker device option requires more specialized technical knowledge, especially in device configuration and integration. On the other hand, the conventional automation and VPN device option may be relatively simpler to implement, as it relies on automation devices with established protocols and interfaces [6].

Evaluation of the pros and cons of each option considering aspects such as cost, complexity, technical requirements, and technical problems [12]:

The IIoT Device and MQTT Broker option has the following points to consider:

Pros:

- Real-time communication: Allows real-time data exchange between the physical machine and the digital twin, enabling immediate response to changes in the stone-cutting machine [2].
- Scalability: IIoT devices can be easily added to or removed from the network, allowing flexible system expansion [6].
- Efficiency: Communication via MQTT Broker is efficient and optimized for message transfer [18].

Cons:

- Technical complexity: Implementing this option requires specialized technical knowledge, both in the configuration and integration of IIoT devices and in the proper configuration of the MQTT Broker [6], [18].
- Initial cost: IIoT devices and MQTT Broker may have a higher initial cost, especially if additional devices and resources are needed to meet specific system requirements [6].
- Technical issues: The use of IIoT devices can be subject to issues such as connectivity failures, protocol incompatibility, and interoperability between different devices and systems [6].

The Conventional Automation Devices and VPN option has the following aspects:

Pros:

- Security: The VPN connection establishes an encrypted tunnel that protects the confidentiality and integrity of data during transmission, ensuring a high level of security [4].
- Scalability: Conventional automation infrastructure can be scaled up to handle a larger number of devices, and VPN allows secure connection from different locations, enabling system expansion [9].
- Less technical complexity: The implementation of this option can be relatively simpler since it relies on conventional automation devices with established protocols and interfaces [23].

Cons:

- Communication Speed: Communication speed may be slightly slower than the IIoT and MQTT Broker device option, due to the additional process of encrypting and decrypting the data during transmission over the VPN [9], [18].
- Ongoing cost: Using a VPN can incur ongoing costs, such as VPN service subscriptions and possibly the need for specific hardware to support the VPN connection [12].
- Technical issues: VPN usage may be subject to issues such as improper configuration, connection instabilities, latency, and bandwidth limitations [4], [6].

4. Results

The comparative analysis of the two options for linking the company and the IPL revealed the following advantages and disadvantages:

The advantage of option 1, lies in the real-time communication, allowing immediate data exchange between the physical machine and the digital twin. In addition, scalability is a plus, as IIoT devices can be easily added to or removed from the network. The efficiency of communication via MQTT Broker is also a benefit [2].

However, this option presents technical complexity, requiring specialized knowledge to configure and integrate the IIoT devices and the MQTT Broker. In addition, the initial cost can be higher due to the devices and possible additional requirements. Technical problems, such as connectivity failures and protocol incompatibility, can also occur [6].

For option 2, security is the main advantage of this option, as the VPN connection establishes an encrypted tunnel to protect the data during transmission. Scalability is another advantage, allowing the system to expand. Implementation is relatively simpler as it relies on conventional automation devices with established protocols. However, the communication speed may be slower due to the encryption and decryption process of the data by the VPN. In addition, there may be ongoing costs such as VPN service subscriptions and possible specific hardware requirements. Technical problems such as improper configuration and connection instabilities may also arise [4].

The choice between the options depends on the specific requirements of the project. Aspects such as real-time communication, data security, system scalability, and resource availability must be considered. Each option has its advantages and disadvantages, and the final decision will be based on the priorities and needs of the project at hand [3], [9].

Based on the results of the comparative analysis of the linkage options between the company and the IPL for the implementation of the digital twin of the stone cutting machine, some implications can be highlighted:

- Choosing the appropriate option: Selecting the most appropriate option depends on the specific needs of the project, considering factors such as the need for real-time communication, data security, system scalability, and available resources. Understanding the advantages and disadvantages of each option helps in the decision making for the implementation of the digital twin [2], [24].
- Financial investment: It is important to consider the financial impact of digital twin implementation, considering the upfront and ongoing costs of each option. The option involving IIoT and MQTT Broker devices may have a higher upfront cost, while the conventional automation and VPN device option may incur ongoing VPN-related costs [3].
- Technical complexity: The technical complexity of the implementation should also be considered. The IIoT and MQTT Broker device option may require expertise in device configuration and integration, as well as dealing with potential technical issues related to connectivity and interoperability. On the other hand, the conventional automation and VPN device option may be relatively simpler to implement [10], [11].
- Data security: Data security is a critical aspect of digital twin implementation. The choice of conventional automation devices and VPN offers a higher level of security due to data encryption over the VPN connection, protecting the confidentiality and integrity of the information transmitted [4], [12].
- Scalability and future expansion: The ability to expand and scale the digital twin system in the future is a relevant factor. The option of IIoT and MQTT Broker devices offers greater flexibility to add or remove devices in the network, making it easier to expand the system. On the other hand, the option of conventional automation devices and VPN allows secure connection from different locations, enabling the expansion of the digital twin [6], [9].

In summary, the implications of the results for the implementation of the digital twin of the stone cutting machine involve careful consideration of financial, technical, safety and scalability aspects. The choice of the most appropriate option should be made considering the specific needs and requirements of the project to ensure an efficient and effective implementation of the digital twin [1], [3], [4].

5. Conclusion

In the paper, a comparative study was conducted between two options for connecting the company and the IPL for the implementation of a digital twin of the stone-cutting machine. The two options were analyzed based on relevant criteria such as communication speed, security, scalability, ease of implementation, costs, complexity, and technical requirements.

The first option, which uses IIoT and MQTT Broker devices, enables real-time data exchange between the physical machine and the digital twin. It offers advantages such as real-time communication, scalability, and message transfer efficiency. However, its technical complexity and higher initial cost may be challenges to consider [10].

The second option, which uses conventional automation devices and VPN, stands out because of the security provided by the VPN connection and less technical complexity in implementation. However, the communication speed may be slower due to the encryption process of the data in the VPN, and ongoing costs are associated with the use of VPN [4], [12].

Based on the comparative analysis, it is important to consider project-specific aspects such as the need for real-time communication, data security, system scalability, and available resources. Each option has advantages and disadvantages, and the choice will depend on the project needs and requirements [3].

Implementation of the digital twin of the stone cutting machine requires careful evaluation of these options, considering factors such as financial investment, technical complexity, data security and future scalability. Selecting the most appropriate option will ensure an efficient and effective implementation of the digital twin, contributing to the improvement of the stone cutting process in the industry [2], [3].

Based on the comparative analysis of the two connection options for the digital twin context of the stone cutting machine, it is recommended to carefully consider the specific requirements and needs of the company and the IPL. Both options have advantages and disadvantages in terms of communication speed, security, scalability, and ease of implementation [2].

The first option, using IIoT devices and MQTT broker, provides real-time communication between the physical machine and the digital twin. This approach provides an efficient and scalable connection, enabling data exchange in an agile manner. The use of IIoT devices, such as SIMATIC IOT2050 and OPC Server 6GK1704-1LW61-3AA0 SIMATIC NET IE SOFTNET-S7 LEAN/, together with the MQTT protocol and an MQTT broker, enables secure and reliable data transmission. This option is suitable for environments that require real-time communication and want to take advantage of IIoT technology [14]–[16].

The second option, through conventional automation devices and VPN, offers an additional layer of security by using a VPN to secure the communication between the company and the IPL. This approach ensures the privacy of the transmitted information and provides a high level of security. Using devices such as the SIMATIC S7-1200, CPU 1214C 6ES7214-1AG40-0XB0, together with the SCALANCE M876-4 4G-Router (6GK5876-4AA00-2BA2), enables the secure connection between the networks and the establishment of a VPN tunnel. This option is recommended for environments that prioritize data security and want a reliable solution for establishing a remote connection [4], [19]–[22].

Both options have implications in terms of cost, complexity, and technical requirements. The first option, with IIoT devices and MQTT broker, may require an initial investment in hardware and configuration of the MQTT environment. The second option, with conventional automation devices and VPN, requires the setup of a VPN network infrastructure and may require advanced technical expertise for implementation [4], [6].

Therefore, the choice of the most appropriate option will depend on the organization's priorities in terms of speed, security, scalability, ease of implementation, and budget requirements. It is recommended to carefully evaluate these aspects and consider the specific needs of the deployment environment before making a final decision.

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6. A DIGITAL TWIN-BASED MANUFACTURING SYSTEM FOR ADVANCED TECHNICAL TRAINING

The fourth and final article of this project explores the silent but powerful revolution taking place in the fusion between the virtual and physical worlds in the context of Industry 4.0. The concept of Digital Twin emerges as one of the most significant innovations, acting as a dynamic entity that evolves in parallel with its physical counterpart [5].

This article focuses specifically on the practical and impactful application of this technology in the Stonecut Line machine, a core element of the ornamental stone industry. The detailed virtual representation of this machine not only visualizes the structure itself, but also highlights the complexity and interaction of its mobile components. Powered by real-time data collected through the Open Platform Communications Unified Architecture (OPC-UA) protocol, this representation enables accurate simulations and optimizations [5], [12].

However, the most transformative impact of Digital Twins can reside in the field of Advanced Technical Training. In a world where technology is constantly evolving, the ability to train technicians in a virtual environment that faithfully replicates reality is invaluable. This not only reduces the costs associated with training on real machines, but also provides a safe environment for learning and experimentation [13].

The article deepens the integration of Digital Twins into manufacturing systems, with a particular focus on their role in training engineers and technicians for real-world challenges, especially in the dimensional stone sector. Through the InovMINERAL 4.0 project, it is possible to demonstrate how Digital Twins serve not only as diagnostic tools but also as robust educational platforms. A comprehensive remote training algorithm is introduced that ensures effective, safe, and practical training experiences [4], [13].

As the industry transitions to a more digitalized landscape, proper implementation of Digital Twins in technical training emerges as a critical factor in maintaining competitiveness and fostering innovation. This chapter represents the culmination of a journey of discovery and innovation, uniting various elements of the ongoing digital revolution [5], [13].

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A Digital Twin-Based Manufacturing System for Advanced Technical Training

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Abstract
The fast evolution of Industry 4.0 technologies has led to a new era of manufacturing systems, with Digital Twins at the forefront. These virtual replicas offer invaluable opportunities for simulation and optimization for new manufacturing processes, since their most transformative impact may lie in the realm of Advanced Technical Training. This article dives into the integration of Digital Twins into manufacturing systems, with a particular focus on their role in training engineers and technicians for real-world challenges, especially in the stone sector dimension. Through the InovMINERAL 4.0 project, it is possible to demonstrate how Digital Twins serve not just as diagnostic tools but as robust educational platforms. It was introduced a comprehensive remote training algorithm that ensures effective, secure, and hands-on training experiences. The algorithm covers everything from secure VPN setup to real-time machining simulations, providing a holistic training approach that prepares trainees for the complexities of modern manufacturing. As the industry shifts to a more digitized landscape, the proper implementation of Digital Twins in technical training emerges as a critical factor for maintaining competitiveness and fostering innovation.

Keywords: Digital Twins, Advanced training, Machining, Remote connection, Security&Reliability

1. INTRODUCTION

The ornamental stone industry, which covers the extraction, design, processing, and marketing of natural stones such as marble, granite, and limestone, plays a crucial role in architecture and interior design globally. These stone materials are known for their aesthetics and durability, adorning monuments, buildings, and homes as testimonies to historical wealth. However, in a constantly developing world driven by Industry 4.0 and the increasing integration of technology in all sectors, the ornamental stone industry faces contemporary challenges, addressing to market demands [1].
Intense global competition, changing consumer preferences and growing environmental concerns are shaping the industry. Innovation becomes vital, especially in the assembly and production of complex ornamental stone products. The implementation of digital twin systems, for example, can transform the industry's operation, optimizing extraction, design, processing and marketing, and meeting market demands [2].

1.1. Sustainability goals

Sustainability has also become crucial to the ornamental stone industry, due to its environmental footprint on the extraction phase and stone waste residues generated on the production phase. With a emergent awareness of environmental issues, the natural stone industry is under pressure to adopt more sustainable practices. The integration of advanced technologies can help reduce waste, use resources more efficiently and minimize the environmental impacts of extraction and processing [2]. In this context, the Sustainable Development Goals (SDG) provide a framework for industries, including the ornamental stone sector, to align their operations with global sustainability targets. There is a synergistic relationship between Circular Economy and Industry 4.0 in achieving SDG, particularly in promoting SDG 12 - Responsible consumption and production [3]. Furthermore, the emphasis on SDG 8 - Decent work and economic growth and SDG 9 - Industry, innovation, and infrastructure resonates with the ornamental stone industry's pursuit of economic growth through innovation and infrastructure development [4]. Small and medium-sized enterprises can leverage cluster management organizations to integrate SDG into their operations, showcasing the adaptability and relevance of these goals across different business scales [5].
On top of that, the SDG 4 should be highlighted, focusing on quality education in fostering innovation skills for engineers in the Industry 4.0 era, underscoring the need for continuous training and adaptability [4].

1.2. Technical training enabled by digital twins

The application of digital twins in complex processes and assemblies suggests a growing need for training in emerging technologies. The rapid integration of new technologies into industrial processes requires technicians to be constantly up-to-date, which can be a challenge in terms of time and resources [2], [6].
The collaboration between humans and machines introduces a new dimension to training. It is not just about operating a machine, but about interacting, understanding and optimizing integrated systems. This requires a multidisciplinary approach to training, with technical skills complemented by competences in areas such as artificial intelligence, data analysis and ergonomics [7].
Another challenge is the disparity in the quality and accessibility of technical training in different regions and countries. While some training centers are at the forefront of technology and innovation, others can be outdated, hindering the preparation of graduates for the global market [8]. This disparity underscores the importance of SDG 4 – Quality Education, emphasizing the need for equitable, quality technical education and training opportunities worldwide, ensuring that professionals are equipped to meet the demands of the modern ornamental stone industry [4].
Technical training is an essential pillar in the advancement of various industries, including the ornamental stone industry. The ability to understand and apply technical knowledge is crucial to ensuring efficiency, precision and innovation in industrial processes. Technical expertise is essential for implementing advanced technologies such as digital twins. The complexity associated with the assembly of mechanical products and the need for accurate data collection and management are highlighted points. In the stone industry, technical training must address the growing complexity of operations, from extraction to processing and marketing. Rapid technological evolution requires constant updating of skills and knowledge, making continuous training essential [2].
As machines become more autonomous, technicians need to learn to collaborate with them, understanding their capabilities and limitations. This requires a training approach that not only imparts technical knowledge, but also interpersonal and collaboration skills. Training programs often fail to keep up with rapid changes in the sector, resulting in a gap between what is taught

and what is needed. This gap can lead to inefficiencies, errors and delays, affecting productivity and innovation [9].
The concept of Digital Twin gained prominence in the recent technological and industrial landscape, emerging as one of the key innovations associated with Industry 4.0. This technology was explored in depth when developing a simulation and monitoring system for milling machining on robots. In essence, a Digital Twin is a virtual and dynamic representation of a physical object or system, allowing for the simulation, analysis and optimization of processes in a controlled environment [10].
The implementation of Digital Twins can revolutionize the way learners interact with and understand complex systems. Instead of relying exclusively on physical equipment, trainees can interact with virtual models, exploring different scenarios, testing solutions and learning from mistakes in a safe and controlled environment. This enriches the learning experience and prepares students for an increasingly digital job market. Integrating Digital Twins into technical training can facilitate the understanding of abstract and complex concepts [2], [7], [11].
It is essential that technical training keeps up with the latest innovations in the field of Digital Twins. This means constantly updating the programs and teaching methods to incorporate the latest advances, ensuring that trainees are prepared for the industry demands [7].

2. DIGITAL TWIN DESIGN

The design of a Digital Twin is an innovative approach that seeks to create a faithful virtual representation of a physical object or system, enabling for simulations, analysis and optimization in a digital environment. This representation is not limited to being a mere digital replica; it is configured as a dynamic entity that evolves in parallel with its physical counterpart, reflecting changes, wear and updates in real time [2].
In this industrial sphere, the design of a Digital Twin plays a fundamental role in optimizing processes, anticipating failures and improving operational efficiency. The accuracy of the virtual model is a cornerstone, since any discrepancy between the digital twin and the physical object can result in erroneous or inefficient decisions. Thus, every component, movement and interaction in the physical system must be thoroughly mapped and represented in the virtual model [12].
The Stonecut Line machine (CEI-Zipor. Portugal) is here considered as a relevant use case for a digital twin focused on training. A detailed 3D representation not only visualizes the machine itself, but also highlights its moving components, allowing an in-depth understanding of their physics, operation and interactions. By identifying and illustrating these components, it is possible to simulate movements, test several operation configurations and anticipate possible failures. Such an approach, not only increases the machine's efficiency, but also extends its service life and reduces the costs associated with unexpected maintenance or failures [13].

2.1. Description of the Stonecut Line machine

The Stonecut Line machine is designed to meet the specific demands of the sector, incorporates technologies to guarantee precise cuts and high-quality finishes in natural stone. The Stonecut Line is able to handle a variety of materials, from delicate marble to tough granite [2], [13].
The 3D representation of the machine provides a detailed breakdown of its construction and design, allowing users and technicians to gain a comprehensive understanding of its functionality and operation. By identifying and visualizing these components, it is possible to gain an in-depth understanding of the physics and engineering behind the real-world machine [10].

The integration of the Digital Twin concept with the Stonecut Line equipment further enhances machine operation and maintenance, thus, creating a cyber-physical system (CPS) [14]–[16]. By creating a virtual representation of the machine, operators can locally or remotely monitor, simulate and optimize performance in real time, leading to continuous improvements and greater efficiency. This innovative approach not only raises standards in the natural stone industry, but also serves as a striking example of the potential of technology when applied strategically [17].
The Stonecut Line is shown in Figure 1 and its simplified 3D representation, stripped from all covers and protections, is shown in Figure 2.

Figure 1: Stonecut Line physical machine.

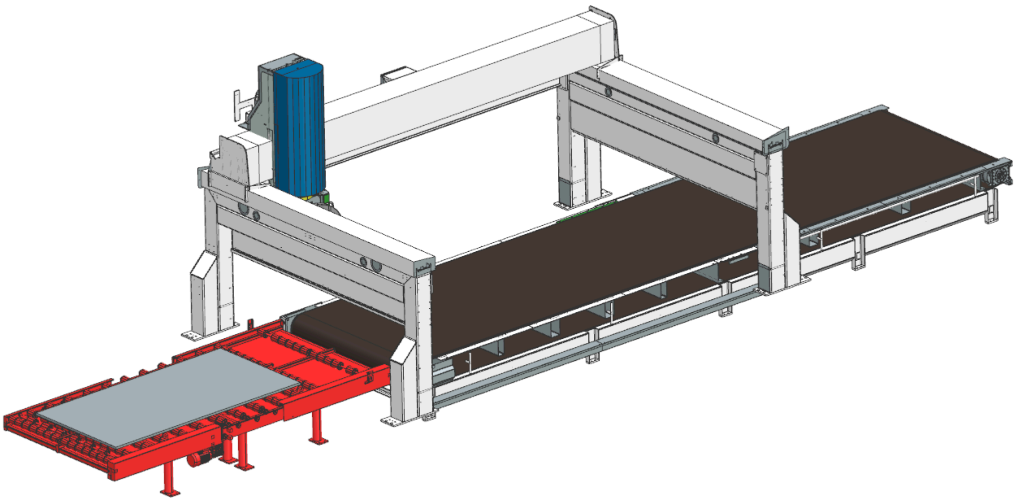

Figure 2: Stonecut Line simplified 3D model.

The Stonecut Line equipment is a gantry machine and it possesses 3 linear axes of movement (X, Y and Z) and 2 rotational axes (B and C). This virtual representation is essential for training, simulation and planning, allowing operators and technicians to visualize and interact with the machine in a controlled environment before actual operation [7].
Among the moving components, the Cutting Tool plays a crucial role, featuring a cutting disk capable of rotating up to 45 degrees on the B-axis, it gives cutting versatility, allowing for precise angled cuts. This flexibility is vital for creating specific designs and finishes in ornamental stones.
The Cutting Head supports and provides motion to the cutting disk. Equipped with 360 degrees rotation capability on the C-axis, it enables multi-directional cuts, increasing efficiency and reducing processing time. The Z-axis is responsible for vertical movement, ensuring precise depth cuts.
The X-axis motor block, governs the horizontal movement of the machine. This movement is essential for longitudinal and transverse cuts. The gantry, which supports the X-axis Motor Block, provides movement along the Y-axis, making sure that the machine covers the entire surface of the stone.
Finally, the Feed Table and Work Table emerge as fundamental components that support and move the stone plate during the setup for the cutting process. These automated tables ensure that the stone plate is safe and stable, minimizing errors and guaranteeing precise cuts.
Together, these moving components operate in harmony to transform raw stone plates into stone parts.

2.2. Mechatronic Concept Design

The Siemens NX Mechatronic Concept Design 1946.4020 wntx64 (Siemens Digital Industries Software, Germany) represents an integrated approach that brings together the principles of mechanics, electronics and computer science to develop more efficient and adaptable systems [18]. This approach is of paramount importance in the context of Industry 4.0, where integration and interconnection between different domains are essential to optimize processes and improve efficiency [12].
At the heart of mechatronic design lies the idea that mechanical and electronic systems should not be conceived separately. On the contrary, they should be perceived as intrinsic components of a larger system, where each element influences and is influenced by the others. This interdependence requires a design approach that considers the system as a whole, rather than focusing solely on its individual parts. In the context of Digital Twin Design, Mechatronic Concept Design (MCD) is particularly relevant. Digital twins, by their very nature, materialize virtual representations of cyber-physical systems. In order for these representations to be accurate and useful, it is imperative that they not only mirror the physical structure of the system, but also its functionality and behavior [19].
Turning mobile components into Rigid Bodies makes it possible to simulate the behaviour of these elements in a virtual environment. This allows designers and engineers to test various configurations and identify potential problems before they arise in the real world. Furthermore, by incorporating real-time data into the virtual model, it is possible to adjust the design in response to changes in operating conditions. In addition to Rigid Bodies, another vital concept in MCD is Collision Bodies. These serve as the physical boundaries within the virtual environment that interact with the rigid bodies. They are crucial for simulating real-world scenarios where different components might collide or interact in a confined space. Understanding how Collision Bodies behave in a virtual setting can provide invaluable insights into how to design systems that are both efficient and safe. This feature is particularly useful

for complex machinery like the Stone Cut Line equipment, where multiple moving parts operate in close proximity [2]. Figure 3 shows the Rigid Bodies, Collision Bodies and motion directions identified on the Stonecut Line equipment.

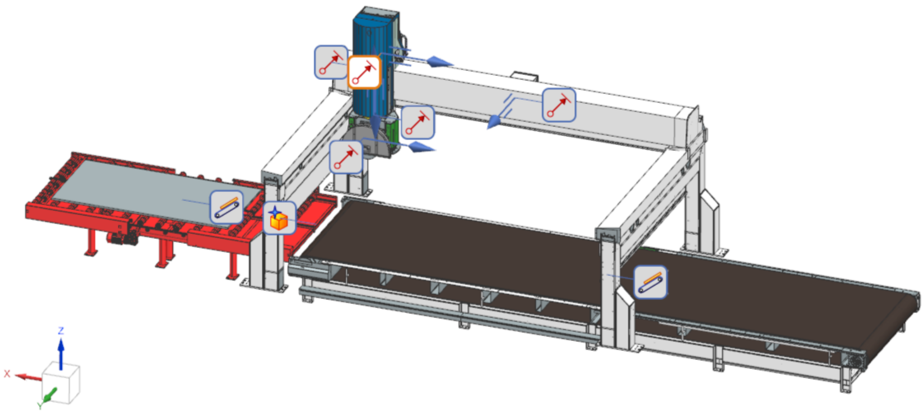

Figure 3: Stone Cut physics defined on MCD.

The concept of remote training represents another crucial aspect of MCD. In an increasingly digitalized world, the ability to provide remote training and education is crucial. By integrating digital twins into remote training platforms, it is possible to connect the digital twin to physical Programmable Logic Controllers (PLC), providing a richer and more engaging learning experience, where students can interact with virtual models of real systems [20].

2.3. OPC-UA Connection Protocol in Digital Implementation

The OPC Unified Architecture (OPC-UA) has emerged as a cornerstone in the realm of industrial automation, offering a secure and reliable framework for data exchange across a multitude of devices and systems. Its platform-agnostic nature ensures seamless interoperability, thereby enhancing the versatility of industrial setups. This is particularly beneficial in the context of Digital Twins, where real-time data collection and transmission are critical for accurate simulation and control [2].
Inoserver, a robust tool designed for real-time data collection, leverages the OPC-UA protocol to gather raw data from various devices located on a specific equipment such as sensors and actuators. This data is then converted into a format that can be easily interpreted by other software platforms like Siemens MCD. The use of OPC-UA in this context eliminates potential bottlenecks and data translation issues, which are common pitfalls when utilizing less efficient communication protocols [21].
On the receiving end, a cockpit equipped with an OPC server is configured to interpret the data transmitted by Inoserver. The MCD software within the cockpit uses this data to simulate the machine's behavior in real-time. This setup ensures that users interacting with the Digital Twin have an experience that closely mimics operating the actual machine. The integration of the OPC server with the OPC-UA protocol ensures that data is received and processed in real-time, providing a fluid and accurate simulation experience [2], [21].

2.4. Electrical Configurations using Signal Adapter

In manufacturing and simulation, electrical configurations are essential for the accurate and efficient operation of complex machinery. MCD incorporates a Signal Adapter to facilitate the integration of these configurations, operating as an intermediary between the physical machine and its digital representation [2], [22].

The Inoserver, utilizing the OPC-UA protocol, serves as a critical intermediary between the physical machine and its digital twin in MCD. It translates raw signals from the machine into a standardized format that can be interpreted and manipulated by the MCD software. This is especially vital for complex systems like the Stonecut Line machine, which continuously generates multiple signals related to position, velocity, and other operational parameters [2]. Within the MCD environment, signal allocation is performed precisely, each signal, whether related to position, velocity or any other parameter, is mapped to a specific component in the 3D model. This association is accomplished through intuitive user interfaces, allowing engineers to map each signal to a specific component or function within the software. This meticulous allocation ensures that, during simulation, the movement of each axis is precisely controlled and monitored, reflecting real operating conditions [10].

Consider the example where the machine sends velocity data in the form of V_z, V_y, V_z vectors. the Signal Adapter employs vector calculation formulas to determine the resultant velocity magnitude. Specifically, the magnitude of the resultant velocity V_f can be calculated using Equation 1.

$$V_f = \sqrt{{V_x}^2 + {V_y}^2 + {V_z}^2} \qquad (1)$$

where V_x, V_y and V_z are the vector components along the respective axes. This calculation is pivotal as it allows the MCD software to understand the speed at which each Rigid Body should move along its respective axis. By accurately translating these signals. The Signal Adapter ensures that the virtual representation on MCD mimics the real-world behaviour of the machine [23]. Figure 4 shows the Physics Navigator tab on MCD, where the electrical input signals for sensors and actuators are pre-configured.

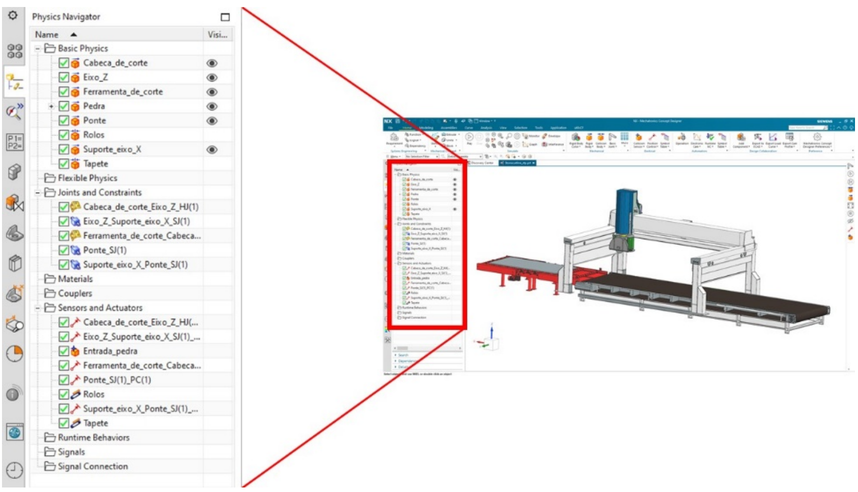

Figure 4: Stone Cut physics defined on MCD.

The integration of electrical configurations via the Signal Adapter offers several advantages. Real-time feedback is provided to the MCD software as the machine operates, enabling instantaneous adjustments and optimizations. This real-time data translation enhances the accuracy of the motion replica conducted in MCD, leading to more reliable predictive models. Furthermore, the proper translation and interpretation of electrical signals ensure that the system operates at optimal efficiency. Discrepancies between the virtual model and the actual machine can be quickly identified and rectified, reducing downtime and increasing overall productivity [2], [17].

2.5. Digital Twin in the Context of Technical Training

Technological advances have driven countless innovations in various spheres, and technical training in the field of ornamental stone is no exception. The implementation of the digital twin focused on training is presented in Figure 5. The Stonecut Line machine is connected to the Inoserver software platform, available at an ornamental stone company, that provides information for this specific equipment under the OPC-UA protocol. At the training facility, a cockpit is installed, consisting on a PC equipped with OPC Server and MCD software packages. The secure peer-to-peer connection between the machine and the cockpit is established through a VPN network, supported by routers at both ends.
While PLC (Programmable Logic Controllers) may not be included in this basic setup, their addition could enhance system security and real-time control. However, given the bilateral data exchange between the school and the company, the existing security measures of the routers are deemed sufficient. Moreover, both the Inoserver and the OPC Server are fully capable of handling the data volume, making the PLC addition as optional in this context [24].

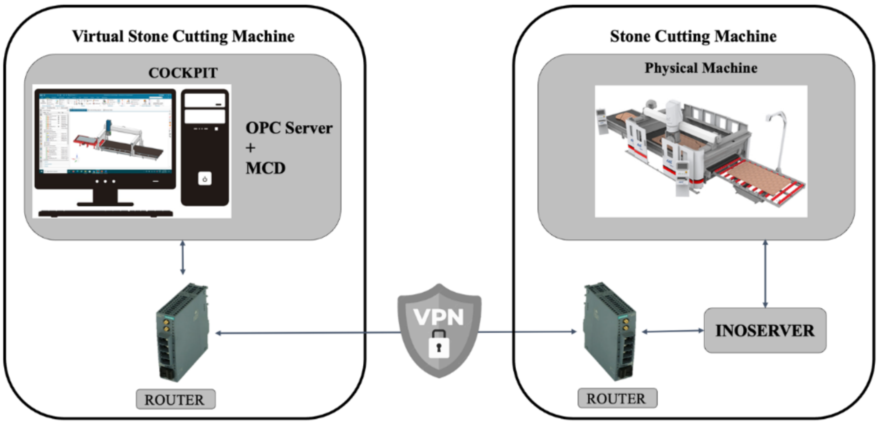

Figure 5: Peer-to-Peer Digital Twin Network for the Stonecut Line equipment.

The schematics presented above show the possibility of this digital twin solution to be used by several stakeholders, in training, equipment condition monitoring and equipment optimization.

2.6. Motion Simulation and Control

Concerning motion simulation and control, the testing of axis movements in digital twin stands out as an essential task. By simulating axis movements, engineers and technicians have the ability to anticipate and identify potential faults, inefficiencies or areas that need adjustment. This predictability is invaluable, as it eliminates the risk associated with testing on real equipment, ensuring that no damage occurs or safety is compromised [10].
The validation methods involves a series of iterative simulations, where each axis movement is tested in different scenarios and conditions. These simulations are often accompanied by comparative analyses, where the results obtained in the virtual environment are compared with historical data or tests carried out in real environments. This approach ensures that digital twin is not only replicating the physical asset, but also accurately predicting axle movements and behaviour [10].
The validation results provide valuable insights. Discrepancies between the simulation and the actual data can indicate areas for improvement in the digital twin model or the motion control algorithms, a close match between the two can serve as a confirmation of the accuracy and

reliability of the virtual model, these results can be used to train technicians, offering them a clear view of the potential challenges and solutions in axis motion control [7].
As well as serving as a diagnostic tool, testing axle movements on Digital Twin also establishes itself as an educational platform. Learners can interact with the virtual model, gaining a practical understanding of the systems and processes, effectively preparing them for real-world challenges in the natural stone industry. Figure 6 encapsulates the journey from initial simulation to hands-on training, underlining the digital twin's invaluable relevance in the world of simulation, analysis, validation and technical education [2], [7], [25].

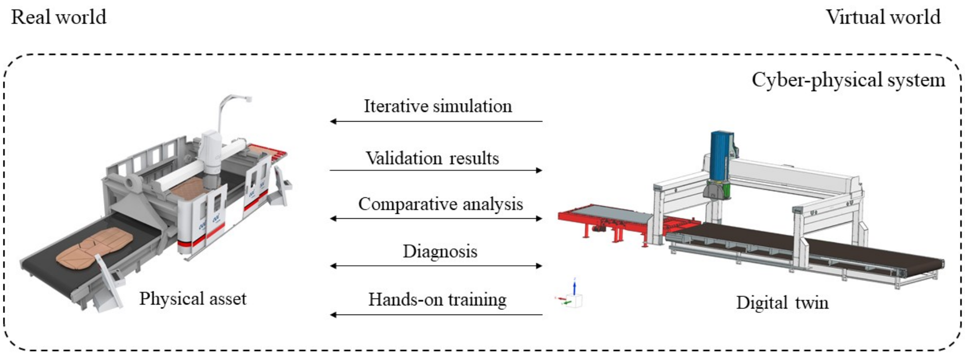

Figure 6: Iterative simulations for motion control on the Stonecut Line equipment.

3. PROCEDURE FOR REMOTE TRAINING

Advanced training in industrial and technical contexts represents an intricate confluence of methodologies, technologies, and operational practices, all converging to ensure maximum effectiveness and safety. In industrial environments, where accuracy and efficiency are imperative, training is not just about transferring knowledge, but also about adapting to new technologies and optimizing existing processes. When preparing for a remote training session that addresses such advanced technologies, it is imperative to consider a few fundamental assumptions that will ensure that the training is not only informative, but also industrially applicable and safe [7], [8].

- Machine and Material Availability: Before starting any training session, it is crucial to ensure that the necessary machine and materials are available and in good working order. This not only facilitates the training process, but also ensures that participants can get hands-on experience during the session [9].
- Connection Security: Connection security is of paramount importance, especially when dealing with sensitive data and real-time operations. A secure connection, protected by strong protocols like VPN and TLS, ensures that data transmitted during the training session is protected from eavesdropping and leaks [26].
- Presence of a Local Operator/Supervisor: Even in remote training sessions, the presence of a local operator or supervisor is essential. They can provide immediate assistance in case of problems, ensure that security procedures are followed, and facilitate communication between remote participants and onsite staff [8].
- Adequate IT Infrastructure: A robust and reliable IT infrastructure is critical to ensuring that the training session runs smoothly. This includes a stable internet connection, compatible hardware and up-to-date software [20].
- Appropriate Training Environment: The environment in which training is conducted should be conducive to learning. This includes ensuring there is adequate space for the

machine and participants, as well as ancillary equipment such as projectors or screens if needed [8].

- Continuous Feedback: During the training session, it is vital to have a real-time feedback system. This allows instructors to tailor training based on participant needs and ensures learning objectives are met [8].
- Documentation and Supporting Resources: Providing participants with supporting materials such as manuals, guides and videos can enrich the training experience. These resources can serve as a reference after the session is complete [8].
- Simulations and Practice: In advanced training, especially those related to machinery and technical operations, practice is essential. Using simulations, especially in a digital twin environment, can give participants a hands-on experience without the risks associated with real-world operations [8].

With geographic, logistical and, more recently, constraints imposed by global emergency situations such as pandemics, traditional on-site training is not always feasible or efficient. This is where remote training comes in, a solution that combines the flexibility of distance learning with the specificity and depth of technical training [20].
Parts machining in particular is an area that requires precision, knowledge and skill, where traditionally this type of training was conducted exclusively on site, with trainees operating machines under the direct supervision of experienced instructors [9]. Advances in digital twin technology and the advanced simulation capabilities offered by software packages such as MCD, it is now possible to replicate this experience in a virtual environment, allowing trainees to learn and practice their machining skills from anywhere in the world [22].
The following algorithm has been developed to guide companies and instructors through the remote part machining training process, ensuring that all critical steps are addressed and that trainees receive thorough and effective training.

1. Remote Connection Setup: Establish a secure VPN connection between the trainee's workstation and the company's network to ensure confidentiality and reliability. Verify connection integrity using strong security protocols such as two-factor authentication and end-to-end encryption [23].

2. Access to the Digital Twin: Allow the trainee to access the stone cutting equipment's digital twin for familiarization. Use the digital twin to simulate the machining process, identifying potential problems or areas for improvement [10], [25].

3. Part Selection and Design: The trainee must choose a part design or be provided with one by the instructor. Using CAD software, the trainee creates a 3D model of the part, which is then reviewed and validated through the digital twin [11].

4. CNC programming: With the help of CAM software, the trainee generates and post-processes the G-code for machining. The code is reviewed in real-time by the instructor using the secure remote connection to ensure accuracy and security [10].

5. Machining Simulation: The trainee runs a simulation in the CAM software, using the digital twin as a reference. Adjustments are made based on simulation results and instructor feedback [25].

6. CNC Machine Preparation: The instructor, physically present at the ornamental stone company, prepares the CNC machine, selecting and installing the appropriate tools.

Machine parameters are configured according to the workpiece material and design specifications [10], [12].

7. Remote Machining: The trainee starts the machining process remotely, supervised in real time by the instructor. Any anomaly is immediately communicated to the trainee, and machining can be paused if necessary [10].

8. Inspection and Feedback: After machining, the instructor physically inspects the part. Trainee and instructor discuss the results, identifying areas of success and areas for improvement [9].

The successful implementation of this algorithm demonstrates the potential of remote training in the industrial sector. Figure 7 serves as a summary of this concept, illustrating the fusion between the virtual training environment provided by the cockpits and the real world, where training facilities held at schools or training centres benefit from the connection to physical equipment, available at ornamental stone companies [8]. Equipment suppliers are also key stakeholders in providing 3D models and physics for the Digital Twin, as represented by the unidirectional arrow towards the cockpit. In addition, they supply physical equipment to companies, ensuring that real machines and their virtual representations are aligned [27].

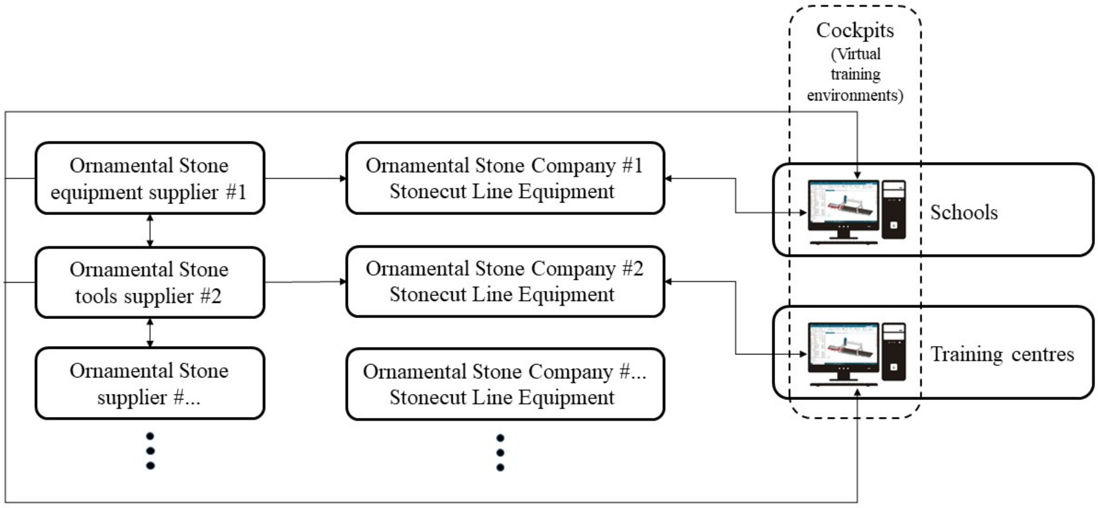

Figure 7: Digital Twin in the context of technical training.

4. CONFIDENTIALITY AND RELIABILITY

The ability to connect to systems and devices remotely offers a wide range of advantages, including flexibility, efficiency and real-time access to data and information. However, with these advantages also come significant challenges related to the confidentiality and reliability of connections [24].
Confidentiality refers to protecting information from being accessed or disclosed to unauthorized parties. In remote connections, this is of paramount importance as the transmitted data may include sensitive information such as operating parameters, simulation data or control information where exposure of this data can lead to a range of risks including industrial espionage, sabotage or misuse. undue information. Therefore, it is essential that remote connections are protected by strong security protocols such as encryption and authentication [24].

In the context of implementing digital twins, as demonstrated in the stone cutting machine, the remote connection plays an even more crucial role. The ability to stream real-time data between the physical machine and its digital twin is critical for monitoring performance, performing predictive maintenance, and virtual simulations. For the implementation of a virtual training environment for a stone cutting machine, it is imperative to ensure that the data transmitted between the company's equipment and the digital twin is protected from interception or leaks [7].

Reliability, on the other hand, refers to the ability of a remote connection to function consistently and accurately without interruptions or failures. In motion simulation and control systems, reliability is crucial, as any interruption or delay in data transmission can result in simulation errors or failures in motion control. This can have significant implications, especially in industrial or production environments where accuracy and consistency are vital [10].

Communication speed, while crucial, can be compromised if reliability and confidentiality are not maintained. A VPN connection can provide an additional security layer, although the encryption process can sometimes slow down data transmission. On the other hand, IIoT devices, although fast, can be vulnerable to attacks if proper security measures are not implemented [24].

With the increasing prevalence of cyber-attacks targeting industrial infrastructure, securing remote connections has become a primary area of focus. Measures such as two-factor authentication, end-to-end encryption and strong firewalls are now standard in most industrial deployments [24].

When implementing digital twin solutions and when establishing remote connections, it is essential to balance the need for speed and efficiency with the imperatives of confidentiality and reliability, choosing the optimal connection solution will depend on the specific needs of the project and the priorities of the organization, but the security and reliability must always be at the heart of these decisions [24], [27].

5. CASE STUDIES: REMOTE TRAINING USING DIGITAL TWIN

Technical training, traditionally based on hands-on and often expensive methods, can now be supplemented and, in some cases, replaced by the use of digital twins operating on virtual environments. This allows trainees to experiment, test and learn in a controlled environment, reducing costs, risks and accelerating the learning process. The ability to receive instant feedback, make adjustments, and repeat processes without the risk associated with real-world operations is invaluable.

Erdei et al (2022) dives deep into designing a digital twin-based training center for an industrial robotic arm. The research highlights the importance of digitally recreating a real environment, including all the complexities associated with a 6-axis industrial robot. The simulation allows for PTP (Point-To-Point), LIN (Linear) and CIRC (Circular) movements, faithfully replicating real-world operations. The integration of the human-machine interface is meticulously designed to provide an immersive experience where users can interact with the virtual robot, program movements and receive instant feedback on possible collisions, inefficiencies or errors [7].

Zhu et al (2023) addresses the simulation of digital twin-based machining for milling robots. This research delves into the technical challenges of digitally replicating the machining process, considering variables such as cutting speeds, feeds, depths of cut and path strategies. The proposed system is not limited to simulation only, but also incorporates a real-time visualization monitoring system. This allows operators to visualize the machining process as it occurs, identifying deviations, errors or inefficiencies in real time [10].

6. CONCLUSIONS

Technological advances and the growing need for integration between the physical and digital worlds have led to the evolution of manufacturing systems based on digital twins. This work presents a detailed analysis of this integration, highlighting its applicability in the context of the InovMINERAL 4.0 project, focused on the training of highly skilled operators.

The implementation of digital twins, as demonstrated, is not just a virtual replica of physical systems, but a powerful tool for simulation, analysis and optimization. The ability to simulate axis movements in a safe and controlled digital environment offers engineers and technicians an invaluable opportunity to anticipate failures, optimize operations and ensure safety. This predictability, coupled with rigorous validation, paves the way for more efficient and innovative manufacturing.

Inoserver's integration with advanced software such as Siemens' MCD demonstrated how real-time data collection and transmission can streamline design and manufacturing. This meticulous integration, which involves precise data conversion and allocation, is critical to advanced simulations and accurate results.

In the context of technical training, the digital twin not only serves as a diagnostic tool, but also as a robust educational platform. The ability to interact with virtual models and simulate operations in real time prepares apprentices for real-world challenges, especially in the dimension stone sector.

Remote connections, while offering flexibility and efficiency, bring with them significant challenges related to confidentiality and reliability. Information security and accuracy of operations are imperative, especially when it comes to advanced technical training. The algorithm presented for remote training in machining parts illustrates the complexity and precision required to ensure training effectiveness.

In conclusion, this work highlights the relevance and potential of digital twins in the modern manufacturing landscape. Through the InovMINERAL 4.0 project, it was possible to demonstrate how the integration of advanced technologies can revolutionize technical training and optimize manufacturing processes. Considering the profound intersection between the virtual and real domains, it becomes indisputable that Digital Twin transcends its identity as a mere technological innovation. It acts as a solid bridge, establishing an intrinsic link between academic theory and hands-on practice, between educational instruction and its tangible materialization in industry. This harmonious confluence of parallel realities unleashes a range of untapped opportunities, catalyzing advances in learning, experimentation and innovation. More than ever, this tool is paving the way to empower the next vanguard of technicians, equipping them with the skills and vision needed to navigate and thrive in the face of the multifaceted challenges and promising opportunities emerging in the dynamic natural stone sector.

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7. General Conclusion

Throughout this project, it was explored in depth the transformative potential of Industry 4.0 and Digital Twin technologies in the ornamental stone industry in Portugal. The InovMINERAL4.0 project was built on the foundations of previous initiatives such as Jetstone, InovSTONE and InovSTONE4.0. These projects have already laid a solid foundation for technological innovation in the sector, and InovMINERAL4.0 aims to extend this trajectory, with a focus on operational efficiency, sustainability, and global presence [1].

InovMINERAL4.0 has much to benefit from the research findings. The insights and strategies presented here are instrumental in the digital transformation of the sector. This synergy between companies, universities and research centers has created an environment conducive to innovation, which in turn has trained professionals and prepared the industry to face future challenges [4].

The ornamental stone industry in Portugal has benefited significantly from the findings presented in this project. Digital transformation is crucial as it directly addresses the Triple Bottom Line principle and affects all environmental, social, and economic elements. The adoption of these advanced technologies has promoted more sustainable practices, reduced waste and driven the evolution of the industry, allowing for greater efficiency and quality [1], [4].

In terms of social impact, the adoption of these advanced technologies promotes more sustainable practices, reducing waste and environmental impact. The industry, on the other hand, gains a competitive advantage in the global market. This evolution gives the industry a prominent position in the global market, with a robust innovation ecosystem ready to face contemporary challenges [7].

Academically, this project fills a critical gap in the literature by providing a holistic view of the application of Industry 4.0 and the Digital Twins in a specific sector. It serves as a reference point for future research and academic endeavors, especially those focused on integrating advanced technologies into traditional industries [5].

Cybersecurity emerges as an indispensable element in the context of this project, especially when we consider the implementation and operation of Digital Twins in the ornamental stone industry. These systems, which function as virtual replicas of physical systems, are intrinsically dependent on a robust and secure IT infrastructure. Any vulnerability in this infrastructure not only compromises the integrity of the Digital Twin but can also have serious implications for the physical system it represents. Therefore, cybersecurity is not just a secondary consideration, but a critical requirement that permeates all phases of the Digital Twin's implementation and operation. Ensuring a secure cyber environment is fundamental to the effectiveness and success of digital transformation in the ornamental stone industry [27].

Article 1 not only sets the scene for the digital transformation of the ornamental stone industry, but also emphasizes the holistic benefits. It serves as a building block for understanding the wider impacts of Industry 4.0. Research into the Portuguese ornamental stone market is an excellent representation of the significance of industrial digitalization. Digital transformation is crucial as it directly addresses the Triple Bottom Line principle and affects all environmental, social, and economic elements. This shows that the Industry 4.0 concept not only addresses technological improvements and industrial principles, but also addresses dedicated sectors holistically.

The second article demystifies the complexities of the Digital Twins and highlights their practical benefits. It serves as a guide for companies looking to adopt this technology for operational efficiency and cost-effectiveness. Digital twin technology may seem like an overly complex simulation, but if applied correctly, it can save a significant amount of time and money when designing prototypes. Digital twins are particularly useful for saving costs, as they allow a holistic view of physical processes. Digital Twin technology is likely to play an increasingly important role in the future of industry.

Article 3 is a practical guide to implementing Digital Twins, especially in machinery such as stone cutting machines. It provides a comparative analysis of connectivity options, emphasizing the need for a balanced approach considering speed, safety, and scalability. The implementation of the stone cutting machine's digital twin requires a careful evaluation of these options, considering factors such as financial investment, technical complexity, data security and future scalability.

Finally, the fourth article focuses on the educational aspect, showing how Digital Twins can serve as advanced technical training tools. It highlights the future of workforce training, making it more interactive, efficient, and secure. Technological advances and the growing need for integration between the physical and digital worlds have contributed to the evolution of manufacturing systems based on digital twins. The implementation of digital twins, as demonstrated, is not only a virtual replica of physical systems, but a powerful tool for simulation, analysis, and optimization.

It is essential to recognize that, as these technologies are adopted on a large scale, cyber security risks increase significantly. Further critical analysis should be carried out to assess the specific vulnerabilities associated with implementing Digital Twins in technical training environments and the potential consequences of a cyber attack in this context. Furthermore, considering the constantly evolving cybersecurity landscape, it is important to recognize that the security measures adopted today may not be sufficient in the future, requiring constant vigilance and updates to maintain system integrity. Therefore, the self-critique of this article should address these potential cyber security concerns.

This project represents a significant milestone in the understanding and application of Industry 4.0 and Digital Twin technologies in the ornamental stone industry in Portugal. It offers a multifaceted contribution, benefiting companies, the InovMINERAL4.0 project, society, industry, and the academic community. The insights and strategies presented here are instrumental in the digital transformation of the sector, setting a new standard for operational efficiency, sustainability, and global competitiveness. The adoption of these advanced technologies has not only driven the evolution of the industry, enabling greater efficiency and quality, but has also promoted more sustainable practices and reduced waste.

The companies involved in the projects have been able to position themselves as benchmarks in the market, offering high quality products with added value. Collaboration between companies, universities and research centers was also a crucial aspect of the success of these projects. This interdisciplinary collaboration promoted the transfer of knowledge and the training of professionals in the sector, resulting in an industry that is more innovative and prepared to face global challenges.

The InovMINERAL4.0 project and the articles presented in this project provide a valuable roadmap for the sector's digital transformation. They offer practical insights and effective strategies for implementing these advanced technologies.

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Appendix

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The International Journal of Advanced Manufacturing Technology

A Digital Twin-Based Manufacturing System for Advanced Technical Training

--Manuscript Draft--

Manuscript Number:	JAMT-D-23-04325
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Abstract:	The fast evolution of Industry 4.0 technologies has led to a new era of manufacturing systems, with Digital Twins at the forefront. These virtual replicas offer invaluable opportunities for simulation and optimization for new manufacturing processes, since their most transformative impact may lie in the realm of Advanced Technical Training. This article dives into the integration of Digital Twins into manufacturing systems, with a particular focus on their role in training engineers and technicians for real-world challenges, especially in the stone sector dimension. Through the InovMINERAL 4.0 project, it is possible to demonstrate how Digital Twins serve not just as diagnostic tools but as robust educational platforms. It was introduced a comprehensive remote training algorithm that ensures effective, secure, and hands-on training experiences. The algorithm covers everything from secure VPN setup to real-time machining simulations, providing a holistic training approach that prepares trainees for the complexities of modern manufacturing. As the industry shifts to a more digitized landscape, the proper implementation of Digital Twins in technical training emerges as a critical factor for maintaining competitiveness and fostering innovation.
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