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CARBON FOOTPRINT REDUCTION ON MANUFACTURING SMES FROM DIGITAL TECHNOLOGIES

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ABSTRACT

This study explores the impact of digital technology adoption on the carbon footprint of SMEs. Utilizing a framework aligned with the ISO Standard 14040 for Life Cycle Assessment, the research evaluates how different levels of digital maturity of the Portuguese Ornamental Stone SMEs influence KPIs related to energy efficiency, production quality, material utilization, and carbon emissions. Companies are categorized by their Digital Rank, ranging from DR#0 (no digitalization) to DR#4 (advanced digital integration). The findings indicate that higher levels of digital maturity are associated with significant environmental and operational benefits. For instance, companies at the DR#4 level achieve a 35.1% reduction in carbon emissions per unit of output compared to those at DR#0. Additionally, these companies show substantial improvements in energy efficiency, producing more units per kWh and enhanced raw material yield, minimizing waste and optimizing resource use. The results underscore the transformative potential of digital technologies in promoting sustainability and operational efficiency. Companies that integrate advanced digital tools not only reduce their environmental impact but also improve their competitiveness and productivity. This research highlights the necessity of a comprehensive approach to digital transformation, encompassing technological investments, organizational change, and process optimization. The study provides actionable insights for policymakers, industry leaders, and SMEs on leveraging digital technologies to achieve sustainability goals. It emphasizes the critical role of digitalization in supporting the global transition to a low-carbon economy. It suggests avenues for future research to explore further integrated digital strategies and their long-term impacts on sustainability.

Keywords: Digital technologies, Decarbonization, Manufacturing SMEs, Ecological Footprint, Stone Industry

INTRODUCTION

Small and medium enterprises (SMEs) are the backbone of the European Union's economy, representing 99.8% of all enterprises in the non-financial business sector across the EU-27 as of 2022 (Di Bella et al., 2023). These 24.3 million SMEs are vital not only because they provide jobs to over 84.9 million people but also because they supply goods and services to a wide range of customers, from individuals to large organizations (Destefanis et al., 2023). However, despite their smaller individual size, SMEs collectively have a significant environmental impact, contributing notably to global energy-related CO_2 emissions. In 2022, these emissions reached a new peak of over 36.8 gigatonnes (Gt), reflecting a 0.9% increase from the previous year (Cozzi, 2023).

In response to the urgent need to combat climate change, there has been a significant surge in investments in digital technologies across various sectors, notably within the Architecture, Engineering, and Construction (AEC) industry. In 2022 alone, these investments reached over EUR 560 billion, driven by the promise of enhancing operational efficiencies and reducing carbon footprints (Yan et al., 2022). Despite these substantial financial commitments, the tangible impact of digital technologies on carbon emission reductions needs to be clarified. Recent studies indicate that the anticipated global reductions in carbon emissions from digital technology adoption have been minimal (Giulia, 2022).

While digital technologies are widely advocated as critical solutions for achieving environmental sustainability (Aldoseri et al., 2024), their direct effectiveness must be thoroughly understood, particularly in reducing carbon footprints within manufacturing SMEs. This gap underscores the need for more focused research to evaluate the real-world impact of digital technologies on carbon footprint reduction in the SME context. Understanding this impact is crucial, as SMEs represent a significant portion of the global economy, and their collective contribution to carbon emissions is substantial. Consequently, this research aims to bridge this gap by providing a detailed empirical analysis of how digital technology adoption affects the carbon footprints of manufacturing SMEs.

The primary objective of this research is to develop and validate a robust empirical framework designed to assess the impact of digital technologies on carbon footprint reduction in manufacturing SMEs. Central to this framework is the concept of DR, which quantifies the extent of a company's adoption of digital technologies. The framework is structured around KPIs that precisely measure improvements in energy efficiency and reductions in carbon emissions.

By evaluating these KPIs across various levels of digital maturity, this study aims to bridge the existing research gap regarding the real-world effectiveness of digital technologies in reducing carbon footprints within the SME sector. The study's findings contributes significantly to global efforts to combat climate change by demonstrating how SMEs can leverage digital technologies to improve their sustainability. These insights will inform policymakers and industry leaders and provide practical guidance for SMEs on optimizing their digital investments to achieve substantial reductions in their carbon footprint. Ultimately, this research will help position manufacturing SMEs as proactive participants in the global transition towards more sustainable and climate-resilient economies.

THEORETICAL BACKGROUND AND RESEARCH METHODOLOGY

The Paris Agreement, adopted by 195 nations in 2015, is a central commitment to the global effort to combat climate change and mitigate its adverse effects (United Nations, 2015). This agreement sets a strategic goal to significantly reduce global greenhouse gas emissions, aiming to cap the rise in global temperatures at two °C above pre-industrial levels by 2050. Achieving these ambitious targets necessitates innovative approaches across all sectors, including AEC industries, which substantially contribute to global emissions.

The Life Cycle Assessment (LCA) methodology is central to evaluating environmental impacts in the AEC sector, as standardized by ISO 14040:2006 (Tam et al., 2023). This framework provides a structured approach to assessing the environmental impacts associated with all stages of a product's life cycle ensuring consistency and comparability in LCA studies by outlining the systematic procedures for conducting these assessments (Wijeratne et al., 2024).

To address the research gap identified and achieve the study's aim, a comprehensive framework is designed leveraging the principles of LCA and integrating them with the assessment of digital technologies' impact on carbon footprint reduction (Kulinan et al., 2024). This methodology follows a structured approach based on the ISO 14040 standards and encompasses the following key steps:

Description of the Context: This initial phase involves a thorough analysis of the manufacturing SMEs sector within the AEC industry. It includes identifying the current practices, challenges, and opportunities related to digital technology adoption and their environmental implications (Li et al., 2020). Detailed sector-specific factors will be considered, such as the types of digital technologies in use, the scale of operations, and the typical life cycles of products manufactured by these SMEs.

Framework Designing: Building on the contextual analysis, a framework is designed to assess the impact of digital technologies on carbon emissions. This framework will integrate the DR concept, categorizing companies based on their level of digital adoption, from basic to advanced integration. The framework will also outline a set of KPIs aligned with the LCA, providing measurable benchmarks for assessing digital technologies' environmental impacts.

Environmental Impact Assessment: Applying the framework to a representative sample of manufacturing SMEs, detailed assessments to quantify the environmental impacts associated with different levels of digital technology adoption will be conducted. Data will be collected through surveys, on-site evaluations, and digital audits. This data will be used to calculate the carbon emissions at each stage of the product life cycle, enabling a comparison between varying levels of digital integration.

Results Interpretation: The final phase involves interpreting the results to draw meaningful conclusions about the relationship between digital technology adoption and carbon footprint reduction in manufacturing SMEs. This step includes analyzing the KPIs to identify trends and insights and providing recommendations for stakeholders on optimizing digital technology investments to enhance sustainability. The findings will be contextualized within the broader goals of the Paris Agreement, offering strategic guidance for policymakers and industry leaders on leveraging digital technologies for climate action.

By integrating DR assessment into the LCA framework, this research evaluates the direct impacts of digital tools on carbon emissions and explores their broader influence on the efficiency and sustainability of manufacturing processes.

EMPIRICAL CONTEXT, POPULATION, AND SAMPLE

The initial stage in the LCA methodology is defining the purpose and extent of a study, which requires establishing clear boundaries and selecting a representative sample (Verones et al., 2020).

In recent years, the transition to a digital economy, often called Industry 4.0 (I4.0), has gained significant momentum, driven by the proliferation of digital and connectable technologies (Slavic et al., 2024). This transformation has profound implications across various sectors, including AEC. A key component of this digital shift is BIM (Wijeratne et al., 2024). This technology promises to revolutionize the sector by integrating processes and data into a cohesive digital framework to reduce waste and minimize ecological footprints (Hadavi & Alizadehsalehi, 2024).

Despite the rapid advancements and substantial investments in BIM and other digital technologies, their impact on carbon footprint reduction within the AEC sector still needs to be explored. BIM is anticipated to become a mandatory global requirement, aligning procurement models towards low-carbon, zero-waste products (Wijeratne et al., 2024). This anticipated shift underscores the importance of understanding how digital technologies can drive environmental sustainability (Kulinan et al., 2024).

The Portuguese Ornamental Stone sector (OS.Pt) is a compelling case study in this context. Portugal is renowned as a world-class producer of stone products, deeply integrated into the global and competitive AEC supply chain—the OS.Pt comprises numerous SMEs employing over 16,600 people, making it a significant private employer, especially in the country's interior regions (Silva & Pata, 2022).

Traditionally rooted in craftsmanship, the OS.Pt has experienced considerable modernization and growth over the past decades. Since 2004, the sector has seen an average annual growth rate of 5.13% in turnover, generating over a thousand new skilled jobs in the last ten years (Silva, Dionisio, et al., 2020).

The OS.Pt's integration into the AEC supply chain is substantial, with companies typically involved in downstream activities—transforming raw stone materials into finished products for the construction sector. The sector's international presence is robust; in 2019, the OS.Pt exported to 116 countries ranked 9th in global stone trade[1], and positioned Portugal as the second highest per capita in the international stone trade. With exports covering imports by 660% and 45% of these exports going to markets outside Europe, the sector's total turnover reached EUR 1.230 billion, underscoring its economic significance and global reach.

For this research, a representative sample was selected to reflect the diversity of digital maturity levels within the OS.Pt. In 2022, surveys were conducted across 16.2% of the sector's companies, encompassing firms from all eighteen continental districts of Portugal. This sampling approach provides a comprehensive view of the sector, capturing the spectrum of digital adoption and its potential impacts on sustainability practices.

FRAMEWORK DESIGN

It is part of the LCA methodology, a framework designed to assess the environmental impacts of digital technologies on the carbon footprint of SMEs (Tam et al., 2023). This framework is crucial for evaluating how digitalization influences sustainability in the manufacturing sector, particularly within the OS.Pt.

4.1. Digital Rank (DR) Evaluation

To effectively assess the impact of digital technologies, it is essential first to evaluate the digital maturity of each company within the sample. This evaluation was conducted through on-site surveys (in-loco) leading to establishing each company's DR. The

[1] https://www.assimagra.pt/pt/

Digital Rank is categorized into five levels: DR#0: Companies with no digitalization initiatives. DR#1: Companies utilizing a single digital production machine. DR#2: Companies operating with two digital production machines. DR#3: Companies employing at least three digital machines integrated with their Enterprise Resource Planning (ERP) system. DR#4: Companies with more than three digital machines fully integrated collaboratively with the marketplace, aligning with the I4.0 (Ye et al., 2022). This classification allows for a nuanced understanding of how varying levels of digital technology integration affect environmental performance across the sector.

4.2. Energy Efficiency KPI

Energy Efficiency (KPI_{EE}) evaluates how effectively a company utilizes its energy resources to produce goods (Asghari et al., 2024). Energy efficiency is a critical measure of operational performance in the manufacturing sector, as it directly impacts cost control and environmental sustainability (Arowoiya et al., 2024). High energy efficiency signifies that a company can produce more output with less energy, leading to reduced operational costs and lower carbon emissions. KPI_{EE} is a metric for manufacturing companies, especially in energy-intensive sectors like OS.Pt, since it measures how well a company utilizes energy resources relative to its output, it is a key indicator of economic and environmental performance. KPI_{EE} quantifies the amount of output produced per unit of energy consumed, explicitly measuring the number of output units generated per kWh used (Equation 1.). This ratio provides insight into the energy efficiency of a company’s production processes (Irfan et al., 2023). A higher KPI_{EE} value indicates greater efficiency, meaning the company produces more output relative to the energy it consumes.

Equation 2. $KPI_{EE} = Average \frac{\sum(O\_UNITS)}{\sum(E\_CONSUM)}$

Output Units (O_UNITS) refers to the total number of finished products or units produced by the company. It reflects the company's production capacity and operational effectiveness. Accurate measurement of output units is crucial as it serves as the numerator in the efficiency calculation, indicating the volume of production relative to energy usage. Energy Consumption (E_CONSUM) is the total amount of energy consumed by the company over the same period. It includes all forms of energy used in production, such as electricity, gas, and other fuels. Precise energy consumption tracking is essential because it forms the denominator in the KPI_{EE} calculation, influencing the assessment of energy utilization efficiency.

Energy efficiency is particularly important in the OS.Pt due to the energy-intensive nature of stone processing. The sector involves activities such as cutting, polishing, and finishing, which require substantial amounts of energy. Therefore, optimizing energy use can significantly impact operational costs and environmental sustainability.

4.3. First Time Through KPI

The First Time Through (KPI_{FFT}) measures production effectiveness and quality within manufacturing processes. It evaluates production efficiency by assessing the proportion of units produced correctly without requiring any rework (Komkowski et al., 2023). High KPI_{FFT} values indicate that a company's processes are robust and efficient, producing many defect-free units on the first pass (Ye et al., 2022). This metric is essential for minimizing waste, reducing costs, and enhancing operational efficiency. For sectors like OS.Pt, where precision and quality are critical, achieving high KPI_{FFT} values is essential for maintaining competitive advantage and operational excellence. KPI_{FFT} quantifies the ratio of units that successfully pass the production process without rework to the total number of units produced (Equation 2.). It reflects the company's ability to produce high-quality products consistently and efficiently.

Equation 3. $KPI_{FFT} = Average \frac{\Sigma(FTT\_UNITS\_k)}{\Sigma(O\_UNITS\_k)}$

First Time Through Units (FTT_UNITS) represent the count of completed units correctly without needing rework. These units meet all quality and specification requirements on the first pass through the production process. FTT_UNITS is a direct indicator of the efficiency and effectiveness of the production process. Output Units (O_UNITS) refers to the total number of units produced during a specific period. It includes all units, regardless of whether they require rework or meet quality standards on the first pass. The total output provides a comprehensive view of the production volume, allowing for a complete assessment of the process's effectiveness compared to the number of defect-free units.
In the OS.Pt, KPI_{FFT} is particularly significant due to the intricate and precision-dependent nature of stone processing. Processes such as cutting, polishing, and finishing require high accuracy and consistency to meet quality standards without defects. By monitoring and optimizing KPI_{FFT}, companies can enhance their production processes, reduce waste, and improve economic and operational performance.

4.4. Raw-Material Efficiency KPI

Raw-Material Efficiency (KPI_{RMY}) is crucial for assessing how efficiently a company uses its raw materials in production (Silva, Rabadão et al., 2020). This KPI is essential in manufacturing sectors where raw materials constitute a significant portion of the production costs and environmental impact (Wang & Shao, 2023). In essence, KPI_{RMY} measures the material yield—the effectiveness of transforming raw materials into finished products. This KPI is essential for manufacturing companies, especially in sectors like OS.Pt where material costs and waste are significant concerns. It clearly measures how effectively raw materials are converted into finished products, serving as a key indicator of economic and environmental performance. Companies can achieve substantial benefits in cost reduction and sustainability by focusing on improving material efficiency through advanced technologies and process optimization. KPI_{RMY} evaluates the number of output units produced per unit of raw material consumed. It provides a ratio that helps understand how much product is generated from the raw materials used. This ratio directly reflects the material efficiency in the production process (Equation 3.).

Equation 4. $KPI_{RMY} = Average \frac{\Sigma(O\_UNITS\_k)}{\Sigma(M\_CONSUM\_k)}$

Raw Material Consumption (M_CONSUM) represents the total quantity of raw materials used during production. It includes all primary materials and additional inputs

required to produce the finished goods. Precise tracking of raw material consumption is critical as it forms the denominator in the KPI_{RMY} calculation, influencing the assessment of material utilization efficiency.
In the OS.Pt, the efficient use of raw materials is particularly vital due to the high cost and environmental impact associated with stone processing. The sector involves cutting, shaping, and polishing, which are material-intensive and generate significant waste. By monitoring and improving KPI_{RMY}, companies can identify opportunities to optimize their material handling and processing operations, fostering economic and environmental benefits.

4.5. Carbon Footprint Emissions KPI

The Carbon Footprint Emissions ($KPI_{CO2\text{-}Eq}$) measures the environmental impact of a company's production processes regarding greenhouse gas emissions (Hoffmann et al., 2024). $KPI_{CO2\text{-}Eq}$ is a vital metric for manufacturing companies, especially in sectors like OS.Pt, where energy use and carbon emissions are significant concerns. It provides a precise measure of the environmental impact per unit of output, helping companies to assess and manage their carbon footprint effectively.
The CO2-eq/kWh value in Europe varies significantly across countries due to the diverse energy mixes used for electricity generation (Cozzi, 2023). Factors influencing these values include the proportion of renewable energy sources, nuclear power, and fossil fuels in the national energy grid. $KPI_{CO2\text{-}Eq}$ quantifies the amount of CO_2 equivalent emissions produced for every 1000 output units. It focuses on emissions derived from public electricity consumption, relating them to the total production output. This measure helps evaluate how efficiently a company uses its energy resources and its impact on climate change. According to the European Environment Agency (EEA)[2] the European average CO2-eq/kWh is approximately 0.233 kg CO2-eq/kWh. This average can be used as a general factor for calculating the carbon footprint in scenarios where specific national data is unavailable (Equation 4.).

Equation 5. $$KPI_{CO2\text{-}Eq} = Average\,\frac{\Sigma(E\_CONSUM)}{\Sigma(O\_UNITS)}\ x\ 0{,}23314$$

The "E_CONSUM" reflects the company's dependency on energy for its production activities. The "O_UNITS" refers to the total count of finished products or units produced during a given period. The factor 0.23314 represents the average emission intensity of CO_2 from public electricity production, in the OS.Pt sector, which involves energy-intensive processes such as cutting, shaping, and finishing stone products, $KPI_{CO2\text{-}Eq}$ is particularly relevant. The sector's reliance on significant energy inputs means managing and reducing carbon emissions is crucial for environmental sustainability and compliance with regulatory standards. For instance, companies with higher digital integration (DR#3 to DR#4) may implement energy-efficient technologies and automation systems that reduce energy consumption and, consequently, lower CO_2 emissions. These companies are likely to achieve lower $KPI_{CO2\text{-}Eq}$ values than those with less digitalization (DR#0 to DR#1), where older, less efficient equipment may result in higher emissions. By monitoring and optimizing $KPI_{CO2\text{-}Eq}$, companies can identify opportunities to reduce their carbon footprint, improve energy efficiency, and contribute to broader climate action goals.

[2]https://www.eea.europa.eu

ENVIRONMENTAL IMPACT ASSESSMENT

The third stage of the LCA focuses on evaluating the environmental impacts of digital technology adoption among SMEs in the OS.Pt. This stage involves collecting detailed data from companies and analyzing KPIs to understand how varying levels of digital maturity affect their carbon footprint and overall environmental performance. Data collection was conducted through comprehensive on-site surveys, where companies were assessed based on their DR. Each company's operational metrics were evaluated to determine their energy efficiency, rework rates, raw material yield, and CO2 emissions (Table 1).

The analysis revealed distinct variations in performance across the different digital ranks. With no digitalisation initiatives, companies at the DR#0 level could produce 294 units per 1000 kWh of energy consumed. These companies faced high rework rates, with 72.9% of units requiring additional processing, and achieved a raw material yield of 65.7%. Their carbon emissions were the highest among all ranks, at 793 kilograms of CO_2 equivalent (kg CO2-eq) per 1000 units produced. There was a slight improvement for companies at the DR#1 level, which utilize a single digital machine. These firms produced 303 units per 1000 kWh, but their rework rates were higher, with 76.3% of units needing rework. The raw material yield decreased to 63.7%, and CO2 emissions were slightly lower at 769.4 kg CO2-eq per 1000 units.

Significant improvements were observed at the DR#2 level, where companies with two digital machines produced 401 units per 1000 kWh. The rework rate improved, with only 57.1% of units requiring rework, and the raw material yield increased to 69.3%. These companies also substantially reduced CO2 emissions, dropping to 581.4 kg CO2-eq per 1000 units. At the DR#3 level, where companies integrate at least three digital machines with their ERP systems, there was a notable enhancement in performance. These firms produced 589 units per 1000 kWh, significantly reducing rework rates to 19.7%. The raw material yield improved to 77.8%, and CO2 emissions were further reduced to 395.8 kg CO2-eq per 1000 units. Controversially, companies at the DR#4 level, characterized by full digital integration and collaboration with the marketplace, demonstrated the highest levels of efficiency. These companies produced 645 units per 1000 kWh, with only 19.7% of units requiring rework. They achieved the highest raw material yield at 84.9% and the lowest CO2 emissions at 361.5 kg CO2-eq per 1000 units.

These findings, summarized in Table 1, highlight the significant environmental benefits of advancing digital maturity in manufacturing processes.

Table 1. KPIs assessment

Digital Rank	KPI_{EE} (units/1000kWh)	KPI_{FFT} (units/units)	KPI_{RMY} (output/raw_material)	$KPI_{CO2\text{-}Eq}$ (KgCO2-eq/Kunits)
DR#0	29,4	27,1%	65,7%	793,0
DR#1	30,3	23,7%	63,7%	769,4
DR#2	40,1	57,1%	69,3%	581,4
DR#3	58,9	80,3%	77,8%	395,8
DR#4	64,5	81,2%	84,9%	361,5
Average	44,6	53,9%	72,3%	580,2

The assessment indicates a clear correlation between higher digital maturity and enhanced environmental performance. Companies progressing from lower to higher digital ranks exhibit substantial improvements across all KPIs. Energy efficiency, measured by KPI_{EE}, increases significantly, reflecting better utilization of energy resources. Production effectiveness, captured by KPI_{FFT}, shows a dramatic reduction in rework rates, indicating more precise and efficient manufacturing processes. The raw material yield, represented by KPI_{RMY}, improves as digital maturity rises, demonstrating more effective use of raw materials and reduced waste. Lastly, CO_2 emissions, evaluated by $KPI_{CO2\text{-}Eq}$, decrease markedly with higher digital integration, highlighting the role of advanced digital technologies in reducing the carbon footprint of manufacturing activities.

Analytical Insights and Interpretations

This stage of the LCA focuses on analyzing the results to evaluate how effectively the study meets its objectives. The analysis provides insights into how digitalization impacts the environmental performance of SMEs, particularly in the OS.Pt.

The KPI_{EE} shows a positive exponential trend as companies advance in digital maturity. This trend is depicted by the dotted line in Figure 1, which illustrates that higher levels of digital integration lead to substantial improvements in energy efficiency. Companies at DR#4 produce significantly more units per kWh than those at DR#0, indicating that advanced digital technologies enable more efficient energy use.

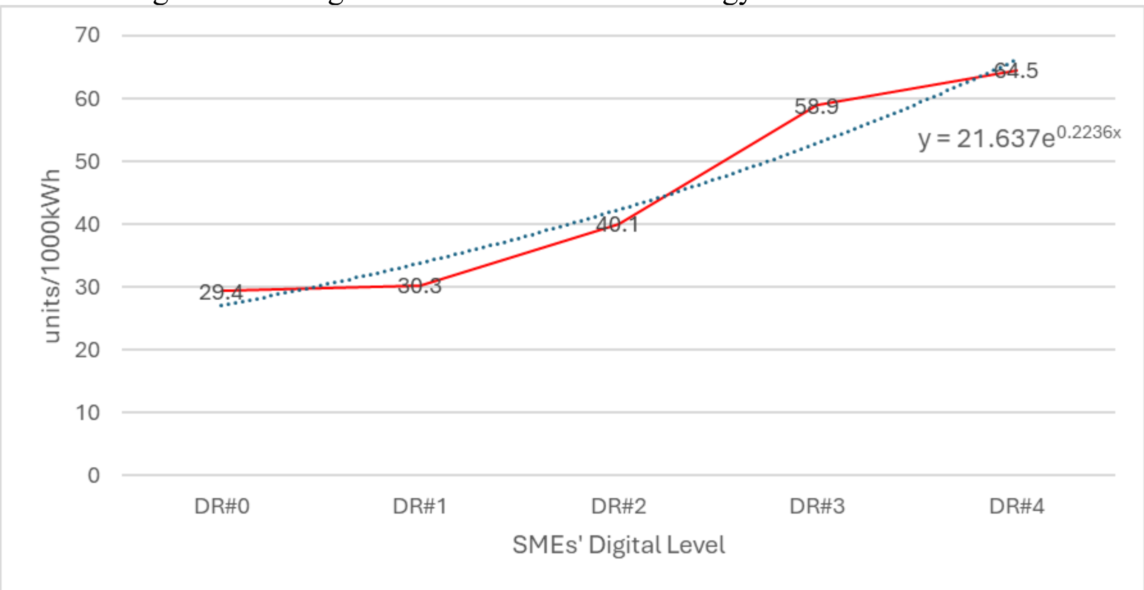

Figure 1. Evolution Trend of Energy Efficiency Across Digital Ranks

This exponential growth in energy efficiency suggests that the benefits of digitalization in reducing energy consumption are amplified as companies invest in more sophisticated technologies. The coefficient value (21.637) of the KPI_{EE} represents the baseline energy efficiency for companies with no digital integration (DR#0). The exponent 0.2236x indicates the growth rate of the KPI_{EE}. A positive exponent means that as a DL increases, the KPI_{EE} increases exponentially.

The KPI_{FFT}, which measures the proportion of units produced without requiring rework, also exhibits a positive trend as companies increase their digital maturity. Unlike the exponential trend observed in energy efficiency, the gains in production effectiveness follow a more linear progression, with an average increase of 16.48% per digital rank. The standard deviation of 0.248 indicates that these gains are consistent across different companies and likely persist over time. This linear improvement in KPI_{FFT} highlights the role of digital technologies in enhancing production quality and reducing defects, thereby minimizing rework and associated costs.

The KPI_{RMY} indicator, which assesses raw material usage efficiency, shows a steady positive trend with increasing digital maturity. Companies that adopt more advanced digital technologies (DR#3 and DR#4) achieve higher material yields, meaning they convert a more significant proportion of raw materials into finished products with less waste. The linear trend gain of 5.05% indicates a consistent reduction in material waste as companies move up the digital ladder. This improvement contributes to carbon footprint reduction and enhances overall productivity and resource efficiency.

The $KPI_{CO2\text{-}Eq}$ indicator measures the carbon emissions per 1000 output units. The data shows an average carbon footprint of 580.2 kg CO2-eq per 1000 pieces across the sample, with a standard deviation of 18.0. This average masks significant differences between digital ranks. Companies at the lowest digital level (DR#0) emit 793 kg CO2-eq per 1000 units, which is 2.19 times higher than the emissions from companies at the highest digital level (DR#4), which emit only 361.5 kg CO2-eq per 1000 units. This stark contrast underscores the potential of digital technologies to reduce carbon emissions drastically and highlights the environmental benefits of advancing digital integration.

By converting energy savings into carbon equivalent reductions, digital technologies play a critical role in lowering the carbon footprint of manufacturing processes. Over five years following investment in digital technologies, the differences between the tiniest and most digitally advanced companies become pronounced. DR#0 companies not only emit more CO_2 but also have higher rates of rework (72.5%) and material waste (34.3%). In contrast, DR#4 companies emit significantly less CO_2 (395.8 kg CO2-eq per 1000 units), have a lower rework rate (19.7%), and waste less raw material (22.2%).

These findings illustrate the transformative impact of digitalization on environmental and operational performance. Companies that invest in and integrate advanced digital technologies can substantially reduce energy consumption, material waste, and carbon emissions while improving production quality and efficiency. The environmental impact assessment confirms that digital technology adoption in the OS.Pt sector leads to significant improvements across all key performance indicators. Companies progressing from lower to higher digital ranks benefit from enhanced energy efficiency, improved production effectiveness, optimized material usage, and reduced carbon emissions. These insights emphasize the importance of digitalization in driving sustainable practices and achieving long-term operational and environmental benefits. As the sector evolves, leveraging advanced digital technologies will be essential for maintaining competitiveness and supporting broader climate action objectives.

CONCLUSION AND FUTURE DIRECTIONS

The primary aim of this research was to evaluate the impact of digital technologies on the carbon footprint reduction of manufacturing SMEs. Using a quantitative

methodology anchored in the ISO Standard 14040 for LCA, a comprehensive framework was designed and applied it to a representative sample of Portuguese stone manufacturing SMEs. The findings from this study provide valuable insights into how different levels of digital technology adoption influence operational and environmental performance, particularly in terms of carbon footprint reduction.
The analysis of KPIs across varying levels of digital maturity reveals two distinct scenarios for potential improvements in carbon footprint and operational efficiency:
Moderate Scenario: An OS.pt SME currently operating with DR#0 that decides to advance to a basic digital maturity level (DR#2) can expect a significant reduction in its carbon footprint of 10.7%. This reduction is supported by a 30.0% decrease in rework rates, reflecting improved production quality and efficiency. Additionally, the OS.pt SME would see a 3.5% gain in raw material yield, indicating more efficient use of resources and reduced waste.

Optimistic Scenario: The potential benefits are even more substantial if the same company opts for a more ambitious investment in digital technologies, reaching an advanced digital maturity level (DR#4). The company could achieve a 35.1% reduction in its carbon footprint. This significant decrease in emissions is accompanied by a 54.1% reduction in rework rates, highlighting the dramatic improvements in production accuracy and defect rates. Moreover, the company would realize a 19.5% increase in raw material yield, demonstrating optimal resource utilization and minimizing waste.
These scenarios illustrate the transformative potential of digital technologies in reducing the environmental impact and enhancing the operational efficiency of manufacturing SMEs. The findings underscore that higher levels of digital integration lead to more significant improvements in energy efficiency, production quality, and material usage, all contributing to substantial reductions in carbon emissions.
The Moderate Scenario offers a practical pathway for companies to begin their digital transformation journey and achieve noticeable environmental and operational gains with relatively modest investments. Conversely, the Optimistic Scenario showcases the significant benefits of comprehensive digital integration, making a compelling case for more substantial investment in digital technologies to maximize sustainability and efficiency.
In conclusion, this research highlights the substantial potential of digital technologies to drive sustainability and efficiency in manufacturing SMEs. As companies navigate their digital transformation journeys, a comprehensive and integrated approach will be essential to realize the full benefits of digitalization. Continued exploration and research in this field will provide deeper insights and support for SMEs aiming to align their operations with sustainable development goals.

Future Research Directions: While this study demonstrates the positive impact of digital technology adoption on carbon footprint reduction, it also suggests that more than simply investing in digital tools may be required to achieve these benefits. The transition to digital operations is complex and requires a multidimensional approach encompassing organizational change, process optimization, and continuous learning. Future research should explore several areas to enhance our understanding of this transition further:

References

Aldoseri, A., Al-Khalifa, K. N., & Hamouda, A. M. (2024). Methodological Approach to Assessing the Current State of Organizations for AI-Based Digital Transformation. *Applied System Innovation*, *7*(1), 14. https://doi.org/10.3390/asi7010014

Arowoiya, V. A., Moehler, R. C., & Fang, Y. (2024). Digital twin technology for thermal comfort and energy efficiency in buildings: A state-of-the-art and future directions. *Energy and Built Environment*, *5*(5), 641–656. https://doi.org/10.1016/j.enbenv.2023.05.004

Asghari, M., Fereidoni, S., Fereidooni, L., Nabisi, M., & Kasaeian, A. (2024). Energy efficiency analysis of applying phase change materials and thermal insulation layers in a building. *Energy and Buildings*, *312*, 114211. https://doi.org/10.1016/j.enbuild.2024.114211

Cozzi, L. (2023). CO2 Emissions in 2022. In *INTERNATIONAL ENERGY AGENCY (IEA)*. https://doi.org/10.1787/12ad1e1a-en

Destefanis, S., Maietta, O. W., Mazzotta, F., & Parisi, L. (2023). Firm survival and innovation: direct and indirect effects of knowledge for SMEs. *Economics of Innovation and New Technology*, 1–29. https://doi.org/10.1080/10438599.2023.2263371

Di Bella, L., Katsinis, A., Lagüera-González, J., Odenthal, L., Hell, M., & Lozar, B. (2023). *Annual Report on European SMEs 2022/2023*.

Hadavi, A., & Alizadehsalehi, S. (2024). From BIM to metaverse for AEC industry. *Automation in Construction*, *160*, 105248. https://doi.org/10.1016/j.autcon.2023.105248

Hoffmann, S., Lasarov, W., Reimers, H., & Trabandt, M. (2024). Carbon footprint tracking apps. Does feedback help reduce carbon emissions? *Journal of Cleaner Production*, *434*, 139981. https://doi.org/10.1016/j.jclepro.2023.139981

Irfan, M., Mahapatra, B., & Shahbaz, M. (2023). Energy efficiency in the Indian transportation sector: effect on carbon emissions. *Environment, Development and Sustainability*, *26*(3), 6653–6676. https://doi.org/10.1007/s10668-023-02981-z

Komkowski, T., Antony, J., Garza-Reyes, J. A., Tortorella, G. L., & Pongboonchai-Empl, T. (2023). The integration of Industry 4.0 and Lean Management: a systematic review and constituting elements perspective. *Total Quality Management & Business Excellence*, *34*(7–8), 1052–1069. https://doi.org/10.1080/14783363.2022.2141107

Kulinan, A. S., Park, M., Aung, P. P. W., Cha, G., & Park, S. (2024). Advancing construction site workforce safety monitoring through BIM and computer vision integration. *Automation in Construction*, *158*, 105227. https://doi.org/10.1016/j.autcon.2023.105227

Li, M., Lu, K., Wang, H., & Wang, S. (2020). Integrating BIM with greenhouse-gas emissions in AEC: A scientometric review. *E3S Web of Conferences*, *143*, 0–4. https://doi.org/10.1051/e3sconf/202014301008

Silva, A., Dionisio, A., & Almeida, I. (2020). Enabling Cyber-Physical Systems for Industry 4.0 operations: A Service Science Perspective. *International Journal of Innovative Technology and Exploring Engineering*, *9*(8), 838–846. https://doi.org/10.35940/ijitee.H6804.069820

Silva, A., & Pata, A. (2022). Value Creation in Technology Service Ecosystems - Empirical Case Study. In J. Machado, F. Soares, J. Trojanowska, V. Ivanov, K.

Antosz, Y. Ren, V. K. Manupati, & A. Pereira (Eds.), *Innovations in Industrial Engeneering II* (pp. 26–36). Springer International Publishing. https://doi.org/doi.org/10.1007/978-3-031-09360-9_3

Silva, A., Rabadão, C., & Capela, C. (2020). Towards Industry 4.0 | A case study of BIM deployment in ornamental stones sector. *International Journal of Innovative Technology and Exploring Engineering (IJITEE)*, *67*, 24535. https://doi.org/ISSN 2307-4531

Slavic, D., Marjanovic, U., Medic, N., Simeunovic, N., & Rakic, S. (2024). The Evaluation of Industry 5.0 Concepts: Social Network Analysis Approach. *Applied Sciences*, *14*(3), 1291. https://doi.org/10.3390/app14031291

Tam, V. W., Zhou, Y., Shen, L., & Le, K. N. (2023). Optimal BIM and LCA integration approach for embodied environmental impact assessment. *Journal of Cleaner Production*, *385*, 135605. https://doi.org/10.1016/j.jclepro.2022.135605

United Nations. (2015). *Conference of the Parties Twenty-first session - ADOPTION OF THE PARIS AGREEMENT: Vol. FCCC/CP/20* (United Nations (ed.); p. 32). United Nations. http://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf

Verones, F., Hellweg, S., Antón, A., Azevedo, L. B., Chaudhary, A., Cosme, N., Cucurachi, S., de Baan, L., Dong, Y., Fantke, P., Golsteijn, L., Hauschild, M., Heijungs, R., Jolliet, O., Juraske, R., Larsen, H., Laurent, A., Mutel, C. L., Margni, M., … Huijbregts, M. A. J. (2020). LC-IMPACT: A regionalized life cycle damage assessment method. *Journal of Industrial Ecology*, *24*(6), 1201–1219. https://doi.org/10.1111/jiec.13018

Wang, L., & Shao, J. (2023). Digital economy, entrepreneurship and energy efficiency. *Energy*, *269*, 126801. https://doi.org/10.1016/j.energy.2023.126801

Wijeratne, P. U., Gunarathna, C., Yang, R. J., Wu, P., Hampson, K., & Shemery, A. (2024). BIM enabler for facilities management: a review of 33 cases. *International Journal of Construction Management*, *24*(3), 251–260. https://doi.org/10.1080/15623599.2023.2222962

Yan, J., Lu, Q., Tang, J., Chen, L., Hong, J., & Broyd, T. (2022). Digital Tools for Revealing and Reducing Carbon Footprint in Infrastructure, Building, and City Scopes. *Buildings*, *12*(8), 1097. https://doi.org/10.3390/buildings12081097

Ye, X., Lu, Y., & Manoharan, S. (2022). Automated conversion of engineering rules: Towards flexible manufacturing collaboration. *Results in Engineering*, *16*(September), 100680. https://doi.org/10.1016/j.rineng.2022.100680