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How digital technologies enhance competitiveness in manufacturing SMEs

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Abstract

This study examines how digital technologies influence the competitiveness of manufacturing small- and medium-sized enterprises (SMEs), with a focus on labor productivity and export performance. Using a sample of 669 firms in the Portuguese ornamental stone sector, a framework was applied to evaluate five levels of digital maturity through a quantitative approach. This analysis covers five years after the investment and combines digital profiling with scenario-based forecasts. Results, presented in figures and tables, indicate a positive link between digital maturity and firm performance, with higher digitalisation levels correlating with increased productivity and export efficiency. For example, the most digitally mature firms experienced labor productivity increase significantly, and their digital investments yielded returns very handsomely for every euro invested. These findings, while illustrative, depend on specific contextual factors and assume ongoing digital adoption. This study offers a replicable model for evaluating digital revolution in traditional industries, supporting SME policy development and strategic planning.

Keywords: Digital technologies, Competitiveness, Manufacturing SMEs, Productivity, Supply chains

Introduction and motivation

SMEs, competitiveness, and digital transformation

Small- and medium-sized enterprises (SMEs) are crucial to the European economy, playing a pivotal role in employment and regional development, and contributing over 20% of jobs, as well as generating significant annual revenues (Smit et al., 2016). In manufacturing sectors, particularly in traditional industries such as ornamental stone, SMEs form the backbone of local production systems and export value chains (Chavez et al., 2022; Radicic et al., 2020), being both critical nodes in supply chains and suppliers of high-value-added products (Cragg et al., 2020). Nevertheless, despite their structural importance, SMEs face considerable barriers to adopting digital technologies, ranging from limited financial and human resources to knowledge gaps and organizational inertia.

Digitalisation challenge and performance uncertainty

Digital technologies offer significant potential to enhance competitiveness through productivity gains, process efficiency, and market expansion. Theoretical frameworks suggest that digital maturity, defined as the degree of digital technology adoption, can significantly impact productivity and export capability (Silva & Gil, 2020). However, the adoption of such technologies, mainly among SMEs remains highly uneven due to financial constraints, workforce limitations, and varying levels of digital readiness (Tian et al., 2023). While some SMEs are advancing toward Industry 4.0, many operate with limited or moderate levels of digital integration, raising concerns about their ability to capitalize on emerging opportunities. Moreover, there is ongoing debate regarding the tangible performance results of digitalisation in SMEs, particularly in traditional manufacturing contexts, where evidence remains fragmented and highly contextual (Yang et al., 2023). Additionally, as global supply chains become more digitized, these challenges endanger the long-term sustainability of SMEs, particularly in sectors such as the Portuguese ornamental stone (OS.Pt) industry (Silva & Almeida, 2020).

Research gap and theoretical relevance

Recent literature highlights key determinants of digital adoption in SMEs, such as top management support, workforce skills, and organizational culture (Faiz et al., 2024). However, it lacks systematic, performance-oriented studies that quantify the outcomes of digital transformation over time. Moreover, few contributions propose structured frameworks that capture the diversity of digital maturity within a single sector and relate it to empirical performance metrics, such as labor productivity and export returns. This is a gap in both academic insights and practical guidance for SMEs and policymakers.

Aim and contribution of the study

This study addresses that gap by examining how digital technologies influence the competitiveness of manufacturing SMEs in the OS.Pt sector. It develops and applies a digital maturity framework that correlates the digital maturity (Amaral & Peças, 2021) of SMEs, classified through a "Digital Rank" (DR) system, with key performance indicators (KPIs), such as labor productivity and export productivity. DR allows firms to be categorized into five levels of technological integration and examines how performance varies across these digital levels.

The main research question, "How do digital technologies impact the competitiveness of manufacturing SMEs?" is examined through theoretical modeling and practical application.

Based on empirical data collected over a five-year study period and scenario modeling, this study contributes to the literature by quantifying the relationship between digital maturity and SME performance and by offering a replicable assessment approach for other traditional industries. It also supports policy and strategic decision-making in promoting digital transformation among SMEs.

Background and related work

Digital technologies are increasingly recognized as key enablers of competitiveness in SMEs, particularly in manufacturing industries facing globalization and innovation pressures. In the European context, SMEs account for approximately 99% of all businesses and make a significant contribution to employment and value creation (Faiz et al., 2024). Yet, their structural characteristics, such as limited financial and human resources (Brodny & Tutak, 2022; Khan et al., 2025), informal management structures, and dependence on external partners (Silva & Marques Cardoso, 2024; Tian et al., 2023), pose significant challenges to the effective adoption of digital tools (Faiz et al., 2024).

In today's global and open market, success in securing orders depends less on company size and more on competitiveness (Spohrer & Kwan, 2009). Competitiveness is commonly defined as a firm or sector's ability to supply goods and services more effectively than others in the same market (Chavez et al., 2022). Labor productivity and export performance are widely used as key indicators to assess competitiveness within global networks (Cragg et al., 2020).

Although interpretations of what it means to achieve competitiveness may differ (Gunasekaran & Ngai, 2004; Rinaldi et al., 2021; Ye et al., 2022), there is widespread agreement on its close connection to manufacturing efficiency, a concept already examined by Adam Smith in the eighteenth century under the term "productivity" (Dallasega et al., 2018). Today, productivity remains a key measure of competitiveness regardless of the nature or volume of resources involved (Hatim et al., 2020).

In the context of increasingly digital and globalized supply chains, customer expectations are evolving toward more innovative (Kiel et al., 2017), environmentally sustainable (Ye et al., 2022), and competitively priced products on a global scale. This shift compels manufacturers to operate as interconnected nodes within complex international networks (Camarinha-Matos et al., 2019), where competitiveness is closely linked to productivity and inherently associated with quality and efficiency (Porter, 1998).

The rapid advancement of digital technologies has had a transformative impact on the global economy, reshaping procurement models for both individuals and organizations (Ibem & Laryea, 2014). Households, businesses, and institutional consumers are progressively fulfilling their needs through digital platforms, accessing a borderless marketplace that facilitates personalized and on-demand solutions (Hatim et al., 2020). This intensification of digital connectivity between producers and consumers contributes to the globalization of supply chains (Hernandez et al., 2017), while market access becomes increasingly contingent upon firms' technological capabilities.

In response to these changes, firms are compelled to undertake comprehensive digital transformations to stay competitive and access international markets. The success of such transformations largely depends on firms' critical mass and capacity for strategic investment (Chen, 2020). However, digitalisation goes beyond merely adopting technology; it involves significant organizational changes, including structural redesign, new production techniques, cultural adaptation, and the development of human capital. As some authors argue, this transformation is no longer optional but a necessity for effective integration into modern, highly competitive global supply chains (Patnayakuni et al., 2002).

These modern supply chains operate as technologically advanced ecosystems, enabling smooth interaction among all stakeholders through intuitive, device-independent digital interfaces (Büyüközkan & Göçer, 2018). Ultimately, such digital infrastructures allow consumers to access the most competitive suppliers worldwide directly, emphasizing the strategic role of digitalisation as a driver of global competitiveness (Cragg et al., 2020).

Within this evolving landscape, several authors emphasize that a firm's competitiveness increasingly depends on its ability to integrate into high-performing, digitally enabled supply chains or networked systems (Patnayakuni et al., 2002; Rinaldi et al., 2021; Vinuesa et al., 2020). Accordingly, such integration becomes a central objective of modern business management, with digital transformation constituting a necessary pathway to achieve it (Tedonchio et al., 2022). Particularly in high-cost regions, such as Europe, the urgency of digital adoption is heightened by the need to maintain a competitive position in global markets (Ye et al., 2022). By embedding themselves within global digital supply chains, firms not only gain access to international customers and suppliers (Kumar et al., 2019) but also improve their operational visibility, agility, and long-term strategic resilience.

Several theoretical frameworks have been developed to analyze technology adoption in SMEs. The Technology–Organization–Environment (TOE) model, developed by Tornatzky and Fleischer (Tornatzky & Fleischer, 1990), highlights three contextual dimensions influencing adoption: technological readiness, organizational capacity, and external environmental pressures. Complementing this, the Diffusion of Innovation (DOI) theory (Garlatti Costa et al., 2025; Rogers, 2003) focuses on the characteristics of innovations and the decision-making process through which they are adopted. Additionally, the Resource-Based View (RBV) framework (Barney, 1991) posits that internal capabilities, such as knowledge, routines, and technological assets, are crucial for achieving and maintaining a competitive advantage. These approaches converge in recognizing that digital adoption in SMEs is not merely a technical issue but is shaped by organizational, strategic, and environmental dynamics.

Despite this theoretical advancement, empirical research remains scattered. While many studies investigate drivers and barriers to adoption, few measure the actual influence of digital technologies on firm performance over time. Some authors (Brodny & Tutak, 2022; Faiz et al., 2024; Vial, 2019), for example, emphasize the importance of managerial awareness, employee skills, and digital culture as determinants of adoption but do not analyze productivity or export outcomes. Similarly, (Jie et al., 2025) reveal that digital maturity has a positive influence on both dynamic capabilities and innovation performance. In the Portuguese context, however, most contributions remain descriptive, lacking sector-specific performance modeling.

Another gap concerns how digital maturity is evaluated. Most frameworks rely on self-assessment tools or qualitative scales, which can be inconsistent or difficult to replicate. Therefore, the concept of digital maturity remains insufficiently defined in empirical research, especially when applied to traditional sectors. Additionally, although scenario modeling is sometimes used for strategic planning, its application in SME-level performance forecasting remains rare. This highlights the need to adopt structured, data-driven methods that link levels of digital adoption with competitiveness outcomes in real-world business environments.

To address these gaps, the present study develops and applies a Digital Rank (DR) framework to classify SMEs into five levels of digital maturity, examining their relationship with labor productivity and export efficiency by applying this framework to a large sample of OS.Pt firms. This study aims to contribute both methodologically and empirically to the literature on digital transformation in manufacturing SMEs over the next five years.

Methodology

A systematic literature review, following (Tashakkori & Creswell, 2007), enabled the determination of firms' current state of digitalisation and identified key performance indicators, as well as the main factors influencing SMEs' digitalisation. The empirical context was then established as the basis for this research. This study adopts a quantitative, data-driven approach to investigate the impact of digital technologies on the competitiveness of manufacturing SMEs, with a focus on labor productivity and export efficiency. The research design is structured in three stages: (i) development of a digital maturity framework (Digital Rank, DR), (ii) classification of firms based on digital intensity, and (iii) comparative performance analysis over a five-year post-investment period.

Conceptual framework and theoretical grounding

The Digital Rank (DR) framework was designed to reflect the variation in digital maturity among firms, drawing on established theoretical models. Specifically, the structure of DR corresponds with the TOE model (Tornatzky & Fleischer, 1990), which identifies three key domains affecting digital adoption: the availability and type of technologies used (technological context), the internal processes and organizational readiness (organizational context), and the links with external stakeholders and markets (environmental context). Furthermore, the framework incorporates aspects from the DOI theory (Rogers, 2003), particularly the roles of relative advantage, complexity, and compatibility in adoption decisions (Garlatti Costa et al., 2025). These models collectively provide a solid foundation for distinguishing firms according to digital level integration.

Data collection and sample

The analysis relies on a structured questionnaire administered to 669 SMEs operating within the OS.Pt sector. The questionnaire was developed in collaboration with industry stakeholders and underwent a pre-test involving 12 firms to ensure clarity and relevance. Although no formal psychometric validation was conducted (for example, Cronbach's alpha), item consistency and instrument logic were checked through iterative consultation with sectoral experts. The data pertain to investments and performance indicators over a five-year period (2016–2020) and include variables, such as workforce size, type and use of digital machinery, adoption of ERP systems, integration with marketplaces, export ratios, and turnover.

Construction of the digital rank (DR)

The DR model categorizes firms into five progressive levels of digital maturity (DR0 to DR4), determined by the presence and combination of three dimensions:

- Technological integration: type of digital-enabled machinery used (CNC, laser, automated cutting).
- Organizational systems: use of Enterprise Resource Planning (ERP), CAD/CAM software, or digital management tools.

– Market linkage: integration with digital marketplaces, platforms or e-commerce channels.

Each level reflects a cumulative degree of digital adoption, a concept that will be explained in greater detail in the following sections: DR0 firms have few or no digital tools; DR1 firms implement isolated technologies; DR2 firms incorporate digital tools into their workflows; DR3 firms connect internal systems to external markets; DR4 firms exhibit fully integrated digital operations. This taxonomy illustrates the increasing complexity, coordination, and strategic use of digital technologies, aligned with the DOI's innovation-decision process and the TOE framework.

Performance indicators and analysis

Two leading performance indicators were utilized: (i) labor productivity (turnover per employee) and (ii) export efficiency (export revenue per euro invested in digital technology). These indicators were selected for their relevance in measuring both operational and international competitiveness. A comparative analysis was carried out across the five DR levels. Descriptive statistics reveal productivity trends, and scenario modeling (optimistic, moderate, pessimistic) was used to forecast potential outcomes over time, assuming linear and non-linear gains based on historical patterns.

Although based on descriptive analysis, this study provides empirical insights into the benefits of digital maturity. Limitations include the use of self-reported data and the absence of advanced statistical testing, which suggests avenues for future research.

Empirical context and framework

This section outlines the empirical and sectoral contexts of the study, followed by the analytical framework employed to evaluate the relationship between digital transformation and SME competitiveness. The aim is to offer a structured overview of how digital maturity was conceptualized, operationalised, and linked to firm performance within the specific context of the OS.Pt industry.

Sectoral context: OS.Pt SMEs

The OS.Pt sector is one of the country's most traditional and export-focused industries, with a strong presence of small- and medium-sized enterprises (SMEs). It plays a vital role in the local economies of regions, such as Alentejo and Centro, having transitioned from a mainly extractive industry to a more diversified value chain that includes transformation, design, and international commercialisation. Accordingly, Portugal is recognized as a world-class producer, fully integrated into the highly competitive and global Architecture, Engineering, and Construction (AEC) supply chain (Silva & Gil, 2020).

Ranked 9th in the world for international stone trade, Portugal was the second country globally in terms of international trade per capita (ASSIMAGRA[1] 2023). It had exports surpassing imports by 660%, with 45% of exports outside Europe, and a total turnover of EUR 1,230 million. Composed mainly of SMEs, the OS.Pt sector is significant to the

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

Portuguese economy, providing over 16,600 direct and indirect jobs and serving as a significant generator of private employment in inland regions.

According to the Portuguese Government[2], the sector has experienced an average annual growth rate of 5.13% over the past decade, with approximately 500 new jobs created since 2016. This growth is linked to several interconnected factors: the technological progress in extraction and processing that significantly improved both efficiency and product quality (Amaral & Peças, 2021) and, additionally, the deployment of a successful international marketing strategy, along with the strengthening of high-value niche products, which helped the sector establish a strong position in global markets.

However, competitiveness challenges remain, especially for smaller firms struggling to keep up with innovation, process optimisation, and international market demands. In this context, digital transformation is recognized as a vital driver for enhancing productivity and expanding global reach, even in sectors often considered traditional or low-tech (Faller & Feldmüller, 2015; OECD, 2019).

Analytical framework: digital maturity and performance pathways

To examine how digitalisation influences SME performance, this study introduces an original analytical framework based on two dimensions: (i) a taxonomy of digital maturity, and (ii) measurable competitiveness outcomes. As referred in section "Background and Related Work", the framework aligns conceptually with the TOE model (Tornatzky & Fleischer, 1990), which provides a multidimensional understanding of digital adoption. It also incorporates key insights from the DOI theory (Rogers, 2003), particularly regarding the incremental and context-sensitive nature of innovation adoption in SMEs (Garlatti Costa et al., 2025).

In sequence, a set of indicators has been developed to evaluate the performance of groups of firms that employ various levels of digital technologies (Tashakkori & Creswell, 2007).

Digital maturity is conceptualized through the Digital Rank (DR), a five-level classification that reflects the degree of digital integration in technological, organizational, and market processes. Meanwhile, performance pathways are defined based on two key indicators of competitiveness: (i) *labor productivity*, measured by turnover per employee in firms with a similar level of digital technologies (Eq. 1), and (ii) *export efficiency*, measured by export revenue per euro invested in digital technologies in firms with a similar level of digital technologies (Eq. 2). These indicators were selected for their ability to reflect both internal operational improvements and external market performance.

$$OS.Pt_{Labour\_DR\#} = \frac{Total\_Sales}{Employees} \tag{1}$$

$$OS.Pt_{Export\_DR\#} = \frac{Total\_Exports}{Employees} \tag{2}$$

[2] https://www.gee.gov.pt/pt/

This differentiation enables the identification of patterns between digital progression and gains in productivity and export performance, thus providing empirical insight into the effectiveness of digital investments over time.

To provide a more detailed analysis of variation and progress, the framework also includes two dispersion indices and two performance gain metrics. The *labor productivity dispersion index* is defined as the standard deviation of labor productivity within a group of firms sharing the same digital maturity level (Eq. 3). Similarly, the *export productivity dispersion index* captures the variation in export efficiency among firms at the same DR level (Eq. 4).

$$OS.Pt\sigma_{Labour} = \frac{\sigma(OS.Pt_{Labour})}{OS.Pt_{Labour}} \tag{3}$$

$$OS.Pt\sigma_{Export} = \frac{\sigma(OS.Pt_{EXPORT})}{OS.Pt_{EXPORT}} \tag{4}$$

Furthermore, the *labor productivity gain* (Eq. 5) and the *export productivity gain* (Eq. 6) measure the marginal performance improvements when a firm progresses by one level in digital maturity. These analytical aspects enable a more detailed understanding of the advantages linked to digital development, beyond simple average comparisons.

$$\Delta.Lab.Prod_{DD\#N} = \frac{OS.Pt_{Lab\_PROD_{DR}\#N}}{OS.Pt_{Lab\_PROD_{DR}\#N-1}}^{\mathrm{N}} = 1, 2, 3, 4 \tag{5}$$

$$\Delta.Exp.Prod_{DD\#N} = \frac{OS.Pt_{Exp\_PROD_{DR}\#N}}{OS.Pt_{Exp\_PROD_{DR}\#N-1}}^{\mathrm{N}} = 1, 2, 3, 4 \tag{6}$$

The analytical assumption is that firms can be meaningfully differentiated based on their level of digital maturity, defined as the extent to which digital technologies are integrated into their operational and strategic routines. This differentiation enables the identification of patterns between digital progression and gains in productivity and export performance, thus providing empirical insight into the effectiveness of digital investments over time.

Digital rank

The Digital Rank (DR) model is a key analytical tool developed in this study to characterize and distinguish SMEs based on their digital maturity levels. It utilizes data gathered through a structured questionnaire and categorizes firms into five levels (from DR0 to DR4), depending on how extensively digital technologies are implemented and integrated into their operations. These levels were defined using three main indicators: (i) the presence of digital technologies in production processes, (ii) the use of management/organizational digital systems, and (iii) the integration of digital tools into commercial and external interaction activities.

The model is cumulative: each level builds on the characteristics of the previous one while adding new features that reflect increasing complexity and digital integration. For example, a firm classified as DR2 utilizes digital tools in production and internal management processes (such as ERP or CAD/CAM), whereas a DR3 firm integrates these internal systems with digital platforms for commercial or logistical purposes. The five levels of the Digital Rank are outlined as follows:

DR0—No Digital: Firms that do not utilize digital technologies in any aspect (production, management, or commercialisation). Their operations are entirely analog.
DR1—Isolated Technologies: Firms that utilize standalone digital tools in production (e.g., CNC machinery, automated cutters) but lack digital integration in management or commercial sectors.
DR2—Internal Integration: Firms that utilize digital systems in production and internal management, operating two computerized machines for at least one year, but without external commercial integration.
DR3—External Connectivity: Firms that employ three or more computerized machines in manufacturing and integrate the information generated by these machines into the Enterprise Resource Planning (ERP) system. These firms can also connect their internal digital processes with external platforms or markets (e.g., B2B or B2C marketplaces, e-commerce systems).
DR4—Full Digital Integration: Firms that demonstrate advanced and consistent digital maturity across all dimensions (production, management, and commercial interfaces) using connected and strategically aligned digital systems. DR#4 represents I4.0 firms (Ye et al., 2022).

The classification was applied to the 669 firms based on their self-reported practices. Each company was surveyed in 2023, with data collection spanning the period from 2021 onwards, thereby avoiding potential distortions caused by the COVID-19 pandemic. The design of the DR was guided by sectoral specificity, expert validation, and alignment with existing digitalisation frameworks, while remaining tailored to the unique features of the OS.Pt industry.

Let us emphasize that the Digital Rank is more than just descriptive: it functions as a structured variable that enables empirical assessment of how varying levels of digital maturity influence performance outcomes, specifically labor productivity and export efficiency. It thus facilitates a nuanced understanding of the returns linked to digital investment and enhances insights into how traditional manufacturing SMEs progress through their digital transformation journeys.

Digital determinants

The empirical development of digital transformation within the OS.Pt sector has been significantly shaped by a series of R&D consortium projects (Silva et al., 2020a, 2020b, 2020c) carried out in collaboration with firms, technological centers, and public agencies. These projects introduced specific technological packages that mark identifiable stages in the sector's digital maturity journey, from reducing raw material waste to enhancing flexibility and enabling a digital alliance with digital marketplaces (Silva & Almeida, 2020; Silva et al., 2020b). In this context, four major "Digital Determinants" (DD) are recognized as crucial facilitators of progress along the Digital Rank (DR) model proposed in this study.

DD#1—*Jetstone*[3] R&D Technologies

The Jetstone R&D project (2004–2007) marked the sector's first significant step toward digitalisation. The technologies introduced during this period aimed to improve manufacturing flexibility and reduce raw material waste (Faller & Feldmüller, 2015). These included programmable cutting systems and the early integration of digital design. Firms adopting Jetstone technologies generally succeed in progressing from DR0 to DR1, thus beginning their digital transformation. The estimated cost for adopting Jetstone technologies over five years is approximately EUR 120,000 (Silva et al., 2020a).

DD#2—*Inovstone* R&D project[4] Technologies

The Inovstone project expanded the scope of digitalisation by enabling SMEs to respond more efficiently to mid-sized custom projects, improving not only material yield but also time-to-market responsiveness (Silva et al., 2020c). The technologies introduced here allowed firms to progress from DR1 to DR2 by integrating ERP systems, CAD/CAM tools, and process automation. The investment associated with Inovstone technologies over five years is estimated at EUR 185,000 (Silva et al., 2020a, 2020b).

DD#3—*Flexstone* R&D project[5] Technologies

Flexstone digital technologies facilitated the transition from DR2 to DR3, emphasizing scalability and project flexibility (Silva et al., 2020a). By elevating DR2 firms, these DD#3 tools enabled OS.Pt firms to manage projects of varying complexity and size, enhance operational efficiency, reduce raw material waste, and respond more easily to shifts in both domestic and international demand. The integration of advanced monitoring and real-time management systems characterizes this stage. The estimated five-year investment is €150,000 (Silva et al., 2020c).

DD#4—*Inovstone 4.0*[6] Technologies

The Inovstone 4.0 project introduced a fully integrated digital ecosystem, combining production, management, and market interfaces (Huang et al., 2022; Silva et al., 2020c). These technologies enable firms to customize products and manufacture projects directly based on Building Information Modeling (BIM) capabilities (Silva et al., 2020b). This suite of technologies allows firms to progress from DR3 to DR4, achieving full digital maturity. Firms at this level can customize production according to market feedback and collaborate in real time with digital platforms. The investment required for Inovstone 4.0 technologies over five years is estimated at EUR 200,000 (Silva et al., 2020a, 2020c).

Besides these four DD, maintaining the DR4 level requires ongoing technological updates, mainly through the integration of new technologies developed by the OS.Pt sector/Academia consortium project *Inovmineral 4.0*[7] These technologies encompass advanced digital management systems and workforce training protocols. To stay

[3] Jetstone—First R&D Project in a consortium to develop disruptive technologies for Ornamental Stones.

[4] Inovstone—Second R&D Project in a consortium to develop disruptive technologies for Ornamental Stones.

[5] Flextone – Third R&D Project in a consortium to develop disruptive technologies for Ornamental Stones.

[6] Inovstone4.0 – fourth R&D Project in a consortium to develop disruptive technologies for Ornamental Stones.

[7] Inovminreal4.0 – fifth R&D Project in a consortium to develop disruptive technologies for Ornamental Stones.

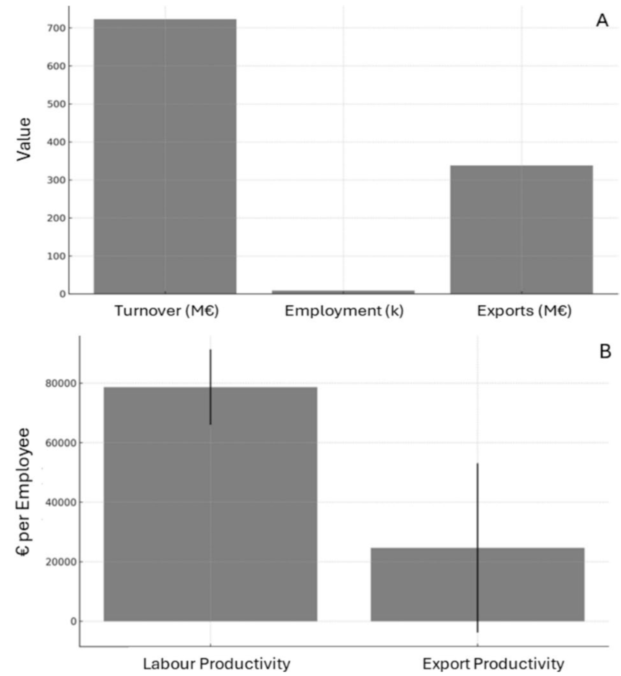

Fig. 1 Aggregate performance (**A**) and productivity levels (**B**) in the OS.Pt sector, based on 2020 data

competitive at this level, a continual investment of around EUR 160,000 is scheduled over five years (Silva et al., 2020a).

These four DD# are not just technological milestones; they illustrate sector-specific innovation pathways that have shaped the empirical structure of the Digital Rank. By linking each level of the DR to concrete innovation programs, the framework gains sectoral validity and methodological strength, thereby bolstering the analytical model underpinning this study.

Data collection and results

Digital maturity as a driver of labor and export productivity in the competitiveness of SMEs

Based on the survey data collected, the 669 firms generated a total global turnover of over EUR 723 million in 2020, employed 8,871 people, and exported over EUR 338 million (Figure 1A); the average labor productivity was EUR 78,621, with a dispersion index of 16.10%, compared to export productivity of EUR 24,671, with a dispersion index of 115.27% (Figure 1B).

Labor productivity, measured as turnover *per* employee, exhibits a clear upward trend across the five DR levels. This indicator reflects internal operational efficiency and is a key performance dimension in the present study. Table 1 summarizes the average labor productivity (OS.Pt_Labor), the matching dispersion (σ_Labor), and the number of firms at each DR level.

Firms at the lowest level of digital maturity (DR0, $n=414$) exhibit an average productivity of €73,964 per employee. This increases progressively through DR1 (€83,009; $n=125$), DR2 (€87,331; $n=90$), DR3 (€90,838; $n=25$), and reaches a peak at DR4 (€96,149; $n=15$). The progression from DR0 to DR4 represents an overall increase of

Table 1 Performance assessment of OS.Pt firms per Digital Rank (DR#)

Digital Rank	*OS.Pt σ_Labour* (EUR)	*OS.Pt σ_Exports* (EUR)	*OS.Pt_Labour* (EUR)	*OS.Pt_Export* (EUR)	*OS.Pt σ_Labour*	*OS.Pt σ_Export*
DR#0	10 861	1 543	73 964	10 862	14,7%	14,2%
DR#1	9 069	18 635	83 009	33 971	10,9%	54,9%
DR#2	12 855	11 276	87 331	61 212	14,7%	18,4%
DR#3	12 795	11 092	90 838 €	81 676	14,1%	13,6%
DR#4	9 418	9 802	96 149 €	93 542	9,8%	10,5%

nearly 30% in average labor productivity, illustrating a strong positive association between digital maturity and operational efficiency.

The *labor productivity dispersion index* (σ_Labor) further supports this trend, decreasing from 14.7% at DR0 to 9.8% at DR4. This indicates that as digital integration becomes more advanced and widespread across operational areas, company performance tends to converge, showing greater uniformity.

The highest dispersion is observed in DR1 (10.9%), likely reflecting its transitional phase, during which firms implement isolated digital tools without strategic integration (Fig. 2). This suggests that DR#1 firms may better align their labor productivity with export productivity. In contrast, the lowest dispersion is observed at DR4, indicating that firms with full digital maturity not only perform better but also do so more consistently and stably.

A comparison between DR0 and DR1 shows a significant shift in export focus among DR1 firms, making them more competitive in the global market. The distribution of labor productivity within DR1 also indicates dynamism, with several firms performing above average. Additionally, the export productivity distribution in this group displays a flat-topped pattern, suggesting a lower concentration and greater spread, which supports the idea of diverse yet upward-trending behavior. Moving from DR0 to DR1 results in an estimated increase of 1.12 times in labor productivity and 3.13 times in export productivity (see Table 2 ahead), underscoring the crucial role of basic digital adoption in boosting export competitiveness.

In DR2, labor productivity exceeds the sample average by 11.1%, with export productivity reaching 148% of the average. Among DR3 firms, labor productivity is 15.5% above the sample average, while export productivity is 2.31 times higher. These improvements emphasize the advantages of more advanced technologies (notably DD#2 and DD#3), which boost production efficiency, minimize waste, and enable greater responsiveness to international market demands.

The dispersion analysis for DR2 firms (Fig. 3A) shows convergence between labor and export productivity distributions, indicating a growing alignment between internal efficiency and external competitiveness. The symmetrical distribution observed in DR3 firms (Fig. 3B), which approaches a Gaussian curve, reflects a more developed competitive stance. Conversely, the vertical orientation of the export productivity distribution signifies a strong international focus. Notably, although labor productivity is higher, DR3

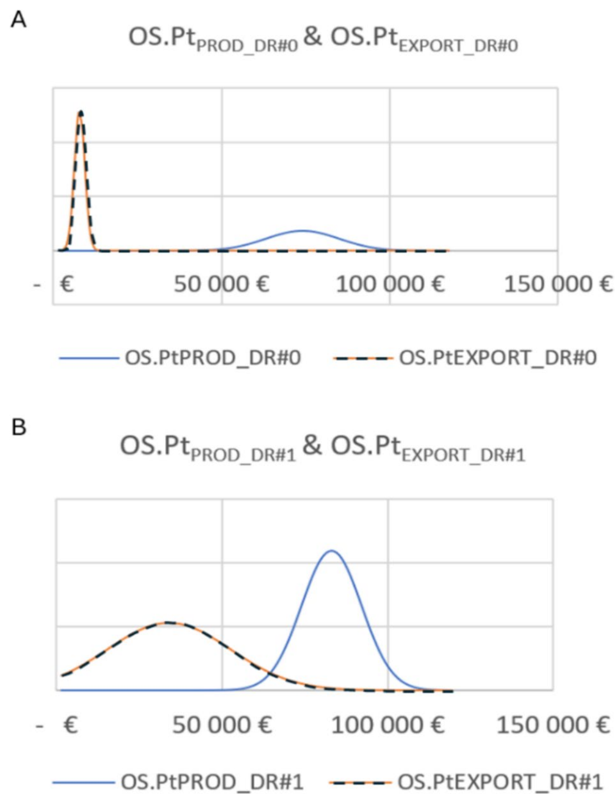

Fig. 2 Normal Dispersion of Labor Productivity and Export Productivity in DR#0 (**A**) and DR#1 (**B**) Os.Pt firms

Table 2 Productivity gains associated with Digital Determinants across Digital Rank transitions

Digital Rank Transition	Digital Determinant	Δ.Lab.Prod$_{DD\#}$	Δ.Exp.Prod$_{DD\#}$
DR0 → DR1	DD#1 – Jetstone	1,12	3,13
DR1 → DR2	DD#2 – Inovstone	1,05	1,80
DR2 → DR3	DD#3 – Flexstone	1,04	1,33
DR3 → DR4	DD#4 – Inovstone4.0	1,06	1,15

firms display a dispersion of 18.4%, which may suggest internal inequalities or that some of these firms are preparing to transition to DR4.

For the 15 firms classified as DR4, labor productivity surpasses the sample average by 22.3%, and export productivity is 2.79 times higher, reaching €68,871 per employee annually (Fig. 4).

The closely overlapping distributions of labor and export productivity in DR4 firms indicate strong internationalization and mature digital alignment. While reduced dispersion suggests stability, it may also imply a risk of stagnation if firms do not continually renew their capabilities. Long-term competitiveness at this stage requires ongoing investment in digital technologies, market development, and human capital.

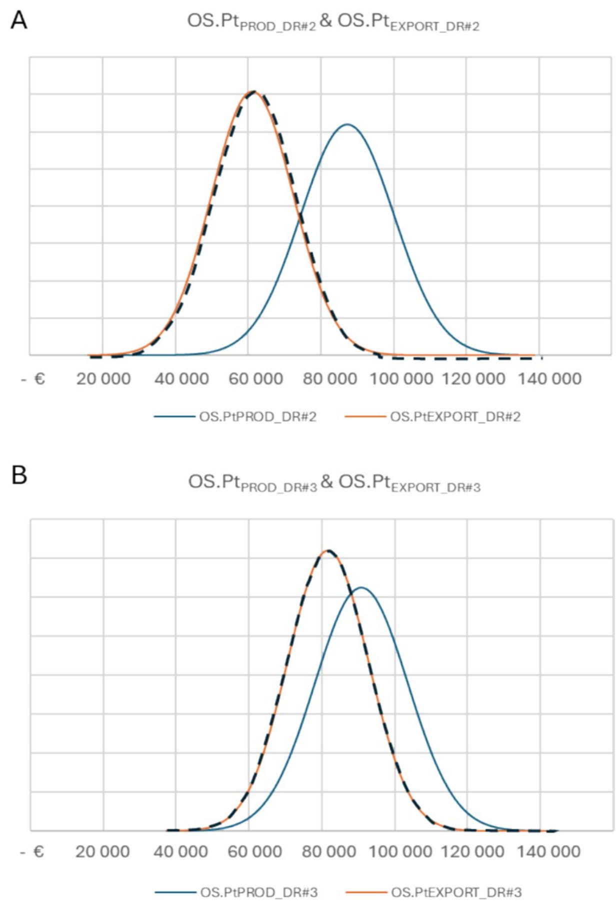

Fig. 3 Normal Dispersion on labor Productivity and export Productivity in DR#2 (**A**) and DR#3 (**B**) OS.Pt firms

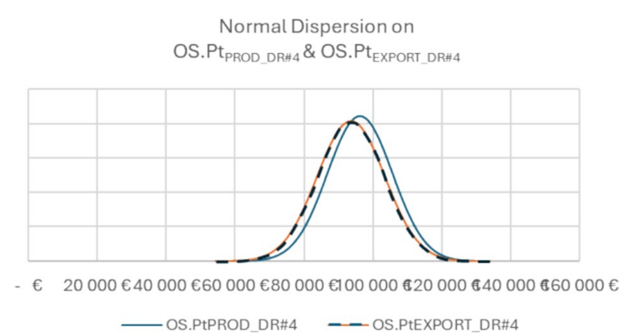

Fig. 4 Normal Dispersion on labor Productivity and export Productivity in DR#4 OS.Pt firms

When assessing productivity improvements related to digital maturity development, investments in digital technologies result in an estimated 1.05 times increase in labor productivity and a 1.80 times higher increase in export productivity from DR2 to DR3. From DR3 to DR4, the gains are 1.04 and 1.33 times higher, respectively (Table 2).

These diminishing returns reveal a key insight: the most significant gains occur during intermediate stages, especially with the adoption of scalable technologies such as those in Flexstone (DD#3). While full integration (DD#4) consolidates performance, it does not significantly amplify marginal returns. Accordingly, firms should consider their digitalisation level when assessing the potential of digital technology investments.

Interpreting digital trajectories: from productivity to strategic positioning

The results demonstrate a strong correlation between digital maturity and firm-level competitiveness, encompassing both operational productivity and export focus. More crucially, the benefits of digitalisation are not linear; they display diminishing marginal returns from DR#2 onwards, especially in labor productivity, while export productivity continues to rise with each DR level.

This pattern suggests that technological depth and integration, as outlined in the DDs, are crucial not only for enhancing productivity but also for maintaining stability across firms. Firms classified as DR#3 and DR#4 exhibit less volatility and more balanced performance distributions, suggesting they have more established positions in international markets.

Although the results indicate a clear positive link between digital maturity and labor productivity, these findings should be viewed with caution. The observed differences may be influenced by unmeasured factors, such as firm size, workforce qualifications, or market orientation. Additionally, since the data are self-reported, potential inaccuracies in reporting must be recognized. Digital implementation is often costly and complex, requiring a significant initial investment and adaptation of the workforce. Firms may encounter integration challenges with legacy systems and temporary productivity drops due to the learning curve associated with new technologies (McKinsey Global Institute, 2021). This underscores the importance of strategic planning, phased implementation, and investing in employee training as vital complements to technological upgrades.

Nevertheless, the steady increase in productivity across digital maturity stages supports the idea that structured digital transformation is connected to operational gains in SMEs, especially in traditional industrial settings. These findings align with recent literature (Faiz et al., 2024; Garlatti Costa et al., 2025), which highlights digital capabilities as vital enablers of efficiency, even when productivity is not directly assessed.

However, the rising costs and organizational challenges of progressing beyond mid-level digital maturity may hinder widespread adoption: most firms might stay at DR1 or DR2, while only a few move toward whole Industry 4.0 maturity. This observed polarization reflects the scenarios discussed in Sect. "Discussion and Conclusion" and emphasizes the need for tailored policies and sector-specific incentives to encourage convergence, rather than divergence, in digital competitiveness pathways.

Competitiveness evaluation

To evaluate the future competitiveness of OS.Pt firms in a digitally evolving industrial landscape, three prospective scenarios were developed: Pessimistic, Moderate, and Optimistic, based on the five years following the initial investment in digital technologies. These scenarios reflect distinct strategic orientations and degrees of digital maturity, grounded in empirical evidence and sector-specific trajectories. They also consider the potential for productivity gains and internationalization associated with each Digital Determinant (DD#) and Digital Rank (DR#) transition.

Table 3 Pessimistic scenario analysis: impact of digital technology investing over 5 years (gain per € invested)

Pessimistic Scenario on OS.pt companies	Impact factor	Five-year period impact
Labour Productivity improvement	0,281	1,41 EUR / EUR
Exports Productivity improvement	0,969	4,84 EUR / EUR

The Pessimistic and Moderate scenarios consider only direct impacts within this 5-year timeframe, while the Optimistic scenario also incorporates indirect effects, thereby capturing potential long-term benefits that extend beyond immediate operational gains, and offering a more comprehensive understanding of how digital technologies can influence market growth, customer engagement, and operational efficiency. This scenario-based approach enables a more detailed understanding of the role of digitalisation in enhancing competitiveness. The impact factor for each scenario is determined based on statistical observations of productivity plateaus of the 669 firms.

A: pessimistic scenario (Digital Conservatism)

In this scenario, a significant portion of Os.pt firms remain at DR0 or DR1, adopting only basic or isolated digital technologies. Investments focus on maintaining existing operations with minimal transformation. As such, firms that mainly adopt DD#1 technologies (Jetstone), produce modest labor productivity gains (1.12 times) and stronger, yet volatile, export gains (3.13 times) (Table 2).

However, the long-term sustainability of these improvements remains uncertain. Insufficient investment in integration and digital alignment increases performance variability (σ_Labor: 14.7% at DR0; 10.9% at DR1) as shown in Table 1 and Fig. 2, which hampers competitiveness.

According to this scenario, labor productivity is projected to decline by 0.281, and export productivity is expected to fall by 0.969. A five-year forecast indicates that investment in digital technologies will boost labor productivity by 1.41 EUR and export productivity by 4.84 EUR per EUR invested (Table 3).

These firms face the risk of stagnation or displacement in international markets, especially as export value creation becomes increasingly reliant on digital interaction, customisation, and marketplace responsiveness.

B: moderate scenario (Digital Convergence)

This scenario foresees a significant shift of firms toward DR2 and DR3, supported by ongoing investment in DD#2 (Inovstone) and DD#3 (Flexstone) technologies. These technologies enhance responsiveness, optimize yields, and increase scalability, allowing firms to manage medium to large-scale projects more efficiently.

The transition from DR1 to DR3 generates gains (Table 2): labor productivity increases, as export productivity, with lower dispersion and an improved export focus. DR3 firms

Table 4 Moderate scenario analysis: impact of digital technology investing over 5 years (gain per € invested)

Moderate Scenario on OS.pt companies	Impact factor	Five-year period impact
Labour Productivity improvement	1,053	5,26 EUR / EUR
Exports Productivity improvement	1,458	7,29 EUR / EUR

approach Gaussian performance distributions (Fig. 3B), suggesting maturity and stability. This is the most strategic inflection point: it balances cost-efficiency, technological integration, and export growth without incurring the full complexity and cost of DR4.

The moderate scenario forecast shows an impact factor of 1.053 on labor productivity and 1.458 on export productivity. Over five years, this scenario shows an impact of EUR 1.41 on labor productivity and EUR 4.84 on export productivity per EUR invested in digital technologies (Table 4).

This scenario benefits from higher productivity, lower costs, and improved customer service, provided that digital technologies are utilized effectively to achieve these goals. It represents the most favorable route to competitiveness on a large scale. It provides a practical progression model for SMEs and aligns with industry trends in similar manufacturing sectors across Europe.

C: optimistic scenario (Digital Vanguardism)

This scenario assumes a more selective progression, in which a small but influential group of firms transitions to DR4 by adopting DD#4 technologies (Inovstone 4.0). These firms achieve the highest levels of labor (€96,149) (Table 1) and export productivity (€68,871) (Fig. 4), with the lowest dispersion (σ_Labor: 9.8%), indicating high consistency in performance (Table 1).

The gains from DR3 to DR4 are positive but less significant, with a 1.06 times increase in labor productivity and a 1.15 times rise in export productivity (Table 2). This transition mainly reinforces competitiveness rather than significantly improving it. Nevertheless, it promotes extensive digital integration across design, production, and market interaction, including BIM-based manufacturing and full connectivity with digital marketplaces.

In the optimistic scenario, the impact factor analysis indicates values of 2.045 for labor productivity and 2.459 for export productivity. Over five years, this results in an expected return of EUR 11.89 in labor productivity and EUR 12.40 in export productivity for every euro invested in digital technologies (Table 5).

However, it is important to note that this scenario is based on several key assumptions: that digital technologies will be applied uniformly across all business sectors, that their adoption will occur at a steady pace, that they will be available at an affordable cost and that the necessary technological infrastructure will be in place.

This third scenario represents the forefront of digital transformation in the Os.pt sector and positions firms for leadership in highly customized, high-value

Table 5 Optimistic scenario analysis: impact of digital technology investing over 5 years (gain per € invested)

Optimistic Scenario on OS.pt companies	Impact factor	Five-year period impact
Labour Productivity improvement	2,045	11,89 EUR / EUR
Exports Productivity improvement	2,459	12,40 EUR / EUR

international markets. However, it demands ongoing reinvestment in technology, staff training, and R&D, and is not easily applicable across the entire Os.pt sector.

In the long run, maintaining a desirable 1% annual growth in service-related activities can significantly improve operational efficiency, revenue, and customer satisfaction (Huang et al., 2022). When applied consistently, such gradual improvements tend to accumulate, fostering a more agile, competitive, and innovation-driven business model (Garlatti Costa et al., 2025). They also enhance organizational flexibility, helping firms stay resilient in changing market environments (McKinsey Global Institute, 2021).

Conversely, not investing in digital technologies raises the risk of falling behind competitors and limits firms' ability to seize emerging opportunities. As shown in Table 5, digital technologies offer a clear competitive advantage, enabling firms to maintain market leadership and prepare for the future.

A comparative overview of the Pessimistic, Moderate, and Optimistic scenarios is provided in Table 6, offering a comprehensive understanding of their trajectories and potential effects on digital competitiveness in Os.Pt firms.

Discussion and conclusion

Micro-, small, and medium enterprises (SMEs) constitute the backbone of most economies. In the European Union (EU), they make up 99% of all businesses, employ around 100 million people, and contribute over half of the EU's GDP (Commission, 2024). Their key role in gross value added and employment across sectors makes them essential for regional development and economic resilience (McKinsey Global Institute, 2021).

Digital technologies improve SMES' ability to respond quickly to environmental changes. Often, structural shifts in the broader institutional and socio-political context, such as regulatory pressures, political realignments, or changes in societal values, serve as key triggers for the adoption of digital technologies (Bennich, 2024; Cragg et al., 2020; Silva & Almeida, 2020). As a result, firms adopt flexible strategies to reduce risks and maintain their legitimacy (Porter & Heppelmann, 2014), and digital technologies help organizational agility, which is defined as a company's "ability to detect opportunities for innovation and seize those competitive market opportunities by assembling requisite assets, knowledge, and relationships with speed and surprise" (Sambamurthy et al., 2003).

Table 6 Strategic Scenarios for Digital Competitiveness in OS.Pt Firms

Scenario	Main DR Levels	Key Technologies (DD#)	Productivity Gains (Labour / Export)	Strategic Implication
A	DR0/ DR1	DD#1 – Jetstone	1.12 / 3.13	Modest gains, high dispersion, stagnation risk
B	DR2/ DR3	DD#2–DD#3 – Inovstone & Flexstone	1.05 / 1.80	Strong gains, balanced growth, scalable competitiveness
C	DR4	DD#4 – Inovstone4.0	1.04 / 1.33	Advanced integration, low dispersion, high investment need

In the context of Industry 4.0 (I4.0), the digital transformation of SMEs becomes even more important as their successful integration into new digital paradigms is vital for ensuring inclusive and sustainable growth in the EU (Bennich, 2024; Commission, 2024).

This study examines the impact of digital technologies on the competitiveness of manufacturing SMEs, with a particular focus on the OS.Pt sector, drawing on the TOE framework developed by Tornatzky and Fleischer (1990). This model has been increasingly applied in recent research exploring the adoption of digital technologies by SMEs (Mittal et al., 2018; Sambamurthy et al., 2003; Yang et al., 2021a). Using a sector-specific digital maturity framework (Digital Rank, DR#0 to DR#4) and data from 669 firms accounting for 83.4% of the national sector, the research analyzed how digital maturity relates to labor productivity and export performance. A quantitative approach was employed to evaluate the progress of productivity across three scenarios of digital competitiveness (Sect. "Competitiveness Evaluation"), providing a comprehensive understanding of how digitalisation supports business growth.

Evidence from this study confirms that digital transformation is a powerful driver of competitiveness in SME manufacturing. On the one hand, it was observed that the adoption of digital technologies is strongly influenced by the technological context in which the OS.Pt firms operate, notably the availability of IT infrastructure and digital tools, as well as the organisation's existing level of innovation, and these results are aligned with those of Jie et al. (2025); Schwaeke et al., 2024; Omrani et al., 2024). Also, it was perceived that internal regulatory frameworks, the availability of skilled human resources, and financial capacity emerge as critical organizational factors shaping the adoption process. These outcomes are aligned with Yang's conclusions (Omrani et al., 2024).

Firms positioned at the highest digital maturity level (DR#4) demonstrated a 22.3% increase in labor productivity and a 2.79 rise in export productivity compared to the sample average. Scenario analysis further revealed that the return on investment (ROI) in digital technologies ranges from EUR 4.84 to EUR 12.40 per euro invested, depending on external market conditions and the level of technological sophistication.

These results reinforce conclusions from earlier studies (Bennich, 2024; Porter & Heppelmann, 2014; Sambamurthy et al., 2003; Yang et al., 2021b) which highlight the role of I4.0 technologies in unlocking firm-level performance gains. More specifically, while the pessimistic scenario suggests a potential 28.1% increase in productivity within five years of digital investment, the optimistic scenario projects a remarkable 204.5% gain. Such projections emphasize the transformative capacity of digital tools, especially for sectors where export intensity and process efficiency are fundamental to competitiveness. Similarly, Edeh's study highlights that policies targeting infrastructure development are critical for enhancing SME capabilities and export performance, while digital technologies are identified as key drivers of overall firm performance (Edeh et al., 2025).

Our findings also align with recent literatures emphasizing the positive relationship between I4.0 adoption and manufacturing productivity (Omrani et al., 2024; Radicic et al., 2020; Smit et al., 2016). They support the argument that digital tools streamline operations, improve integration into supply chains, and enhance responsiveness to market demand. However, this study provides a more detailed, sector-specific assessment by mapping productivity trajectories to specific digital maturity levels and investment profiles, addressing a gap in generalized studies (Amaral & Peças, 2021; Radicic et al., 2020).

Furthermore, this study highlights the specific challenges faced by SMEs, such as resource constraints, workforce readiness, and complexities in digital integration. These insights align with (Khan et al., 2025), which emphasizes the importance of entrepreneurial orientation in helping SMEs leverage digital platforms. Additionally, the framework proposed here complements those who underline the role of digital supply chains in reinforcing global competitiveness (Büyüközkan & Göçer, 2018; Omrani et al., 2024).

Our results highlight the essential role of digital transformation for SMEs seeking to compete on a global scale. In today's digital age, manufacturing firms seek to enhance their competitive advantage by leveraging digital transformation to unlock new opportunities for value creation, circularity, and revenue growth (Goh et al., 2019; Omrani et al., 2024; Vial, 2019). In these cases, they are implementing digital technologies in various domains, such as product design, manufacturing processes, and sales management, to improve product quality, increase production efficiency, and broaden their market reach (Holmström et al., 2019).

Despite these advances, our study recognizes that digital transformation causes disruptions. Often, many OS.Pt SMEs face a paradox: while digital tools generate new value opportunities (e.g., improved product design, efficient sales, and broader markets), barriers, such as high costs, delays in implementation, and integration challenges can limit profitability, as (Goh et al., 2019) and (Maguire et al., 2021) found. Corroborating this, (Hasan et al., 2020) and (Diaz-Basset et al., 2021) showed that 78% of digital transformation projects fail, with issues including poor user adoption and unsustainable returns.

Emerging technologies, such as Artificial Intelligence (AI), present potential solutions. According to Bergamaschi et al. (2021), over 90% of leading service providers already utilize AI, with some reporting productivity increases of up to 30%. For SMEs in high-cost economies like Portugal, AI and other digital tools are not merely advantageous; they are strategic essentials for maintaining relevance in global supply chains.

Overall, this study confirms a strong and measurable link between digital maturity and SME competitiveness. Even modest investments in technologies, such as ERP, CNC automation, or BIM-integrated systems, lead to productivity improvements. In line with (Radicic et al., 2020) and (Omrani et al., 2024), the results underscore the need for targeted public policies, digital innovation hubs, and sector-specific co-financing schemes to support SMEs in their digital upgrades.

This research thus addresses the core question: *How do digital technologies impact the competitiveness of manufacturing SMEs?* By developing and applying a scalable digital maturity model (Digital Rank) and analyzing its correlation with productivity and export metrics, the study offers a clear framework for benchmarking SME performance and informing digital strategy in both policy and management contexts. It demonstrates that structured, incremental digitalisation is essential to transforming traditional industrial sectors into globally competitive ecosystems.

Strengths and Limitations

A key strength of this study is its combination of sector-specific detail and broad empirical coverage. By examining 669 firms, representing 83.4% of the OS.Pt sector, and utilizing a customized Digital Rank (DR#) model, the analysis moves beyond mere theory to deliver a tangible performance mapping that reflects actual digital investments. The incorporation of labor productivity and export performance indicators enhances the assessment of competitiveness. Simultaneously, the adoption of a multi-scenario framework (Sect. "Competitiveness Evaluation") increases the robustness and relevance of the findings across different market conditions.

However, some limitations must be recognized. First, this study's scope is confined to a single manufacturing cluster in Portugal, which, while rich in analysis, may restrict the generalization of findings to other industrial or geographical settings. Second, the research employs a quantitative approach and does not examine qualitative aspects, such as managerial perceptions, organizational resistance to change, or the role of leadership, which could significantly influence the success of digitalisation efforts. Finally, although the Digital Determinants (DD#1–DD#4) are described in detail, the ongoing evolution of technology was not modeled longitudinally, suggesting a potential pathway for future research.

Practical implications

This research offers practical insights for business leaders, policymakers, and innovation intermediaries. For SME managers, the Digital Rank framework serves as a valuable diagnostic tool to assess current digital maturity and identify the most strategic technological upgrades that can deliver performance benefits. Productivity and export improvements associated with each DR level (Sect. "Competitiveness Evaluation") serve as benchmarks for guiding digital investment decisions and managing expectations.

For policymakers and cluster stakeholders, this study underscores the strategic importance of closing gaps between digital frontrunners and laggards. The segmentation of firms by DR# indicates that productivity improvements are unevenly spread, implying that policies should not only encourage innovation but also promote digital inclusion among SMEs. Tools, such as targeted financial incentives, training programmes, and co-financed R&D consortia (e.g., Jetstone, Inovstone, Inovstone 4.0), seem crucial for enhancing sectoral competitiveness, even in disruptive times (Meramveliotakis & Manioudis, 2021).

Moreover, the ROI analysis strengthens the case for public–private partnerships that mitigate risks associated with digital adoption. Export promotion agencies may also use these insights to prioritize support for DR#3 and DR#4 firms that are digitally ready for internationalization, as also referred to by Bergamaschi et al. (2021). Lastly, this study offers a framework that can be copied or tailored for use in other traditional industries seeking to align digitalisation with competitiveness strategies.

Final Remarks

This study aligns with the conclusions presented in the latest OECD (2024) survey on SME Digitalisation to Manage Shocks and Transitions (Commission, 2024) as we found that the transformative potential of digital technologies for manufacturing SMEs enhances labor productivity and export performance. It confirms that digitalisation is a key enabler of competitiveness in traditional manufacturing sectors. This study fills a vital gap in the literature by systematically linking digital maturity levels to measurable competitiveness metrics, offering a clear roadmap for SMEs navigating the digital transformation process.

By establishing a measurable link between digital maturity and firm performance, it also offers a framework that not only evaluates the current state of digital integration but also guides strategic prioritization for SMEs navigating the complexities of Industry 4.0.

The Digital Rank model and its related empirical findings make important contributions both theoretically and practically to the literature on SME digitalisation, providing a scalable, sector-sensitive approach. Ultimately, the results indicate that while digital transformation demands significant investment, effort, and vision, it is also a vital route for SMEs aiming to stay relevant, grow sustainably, and compete on a global scale.

Suggestions for future studies

While this study provides robust empirical evidence of the link between digital maturity and competitiveness in manufacturing SMEs, several avenues for further research arise.

First, future research could take a longitudinal approach to examine how productivity gains from digital investments develop over time. This would enable the analysis of lag effects, the sustainability of performance improvements, and the evolutionary dynamics of digital adoption in traditional sectors.

Second, broadening the scope to include other industrial clusters or different national contexts would facilitate comparative analysis and improve the generalisability of the Digital Rank (DR#) framework. Cross-sector comparisons could demonstrate whether the same patterns of digital gains are valid in sectors with varying levels of capital intensity, regulatory environments, or market structures.

Third, future research could include qualitative aspects by examining the organizational, human, and cultural factors that affect successful digital adoption. Understanding managerial attitudes, employee readiness, and the role of leadership would enhance the explanatory power of digital maturity models and aid in interpreting outlier cases where investment does not result in expected performance improvements.

Furthermore, incorporating emerging technologies, particularly Artificial Intelligence (AI) and advanced data analytics, into future frameworks would be beneficial, given their increasing importance and transformative potential. Research could evaluate not only adoption rates but also the depth of integration, value creation processes, and ethical or organizational trade-offs.

Finally, the relationship between digitalisation and other aspects of sustainability, such as environmental performance, social impact, and resilience, as pinpointed by Maguire et al. (2021), remains underexplored in SME research. Future studies could investigate how digital technologies support or hinder progress toward broader sustainability objectives, including circular economy principles and ESG performance, as also suggested by Hasan et al. (2020).

By advancing research in these areas, scholars can further refine theoretical models, support evidence-based policymaking, and increase the competitiveness and sustainability of SMEs in the digital age.

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Author contributions
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Data availability
The data behind the findings are available from the corresponding author upon reasonable request. The data supporting this study's findings are available from the corresponding author (isabel.cristina.almeida@iscte-iul.pt) upon reasonable request.

Declarations

Competing interests
The authors declare no competing interests.

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