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Insights into Digital Technologies Sustainability and the Economic Performance of Greek Enterprises

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Abstract: This research examines how specific digital technologies—including artificial intelligence (AI) systems based on machine learning algorithms, data analytics platforms for real-time decision support, cloud computing infrastructures, Internet of Things (IoT) sensor network applications, and digital market platforms—affect the economic performance of Greek enterprises. Rather than treating digitalization as a homogeneous input, the analysis explicitly distinguishes between technology types and their application mechanisms within firms. Market-facing technologies (e-commerce systems and digital marketing platforms) operate primarily through demand expansion and market access, while production- and decision-oriented technologies (AI, machine learning-based analytics, IoT sensor networks, and cloud infrastructures) affect performance through process optimization, resource allocation efficiency, and organizational learning. Using a theory-driven and visualization-based analytical framework grounded in enterprise survey evidence, the study evaluates the association between individual and combined technology adoption and key performance indicators, including output growth, labor productivity, and total factor productivity (TFP). The results indicate that AI and data analytics systems enhance productivity through algorithmic optimization and data-driven decision processes, while IoT applications contribute via real-time monitoring, predictive maintenance, and input efficiency improvements. Cloud computing functions as a general-purpose enabling infrastructure, amplifying the productivity effects of other technologies. Enterprises adopting multiple complementary technologies exhibit significantly stronger performance outcomes than single-technology adopters, with multi-technology integration associated with TFP gains of approximately 15–20% in digitally mature firms. The findings highlight that digital transformation improves economic performance primarily through technology-specific application mechanisms and cross-technology complementarities, rather than through generic digital adoption alone.

Keywords: Digital Technologies; Digital Transformation; Enterprise Performance; Productivity; Total Factor Productivity; Economic Growth; Greece; Firm-Level Analysis

1. Introduction

Digital technologies are increasingly adopted by enterprises around the world. Yet empirical studies on their economic impact demonstrate mixed results by country, by sector, and by size. Support for the theory that digitalization leads to improved economic performance is particularly weak for Greece, with only a few analyses available, and only for information and communications technology. The present article addresses this gap by assessing both the extent of adoption and the effects on economic performance of a broader range of digital technologies. Recent special-interest surveys constitute a new, consistent dataset that identifies core technologies, describes their diffusion patterns across sectors, addresses digitalization barriers and drivers, and estimates links with productivity and enterprise growth. Digital technologies also play a role in Greece's digital transformation strategy. An explicit policy goal is to stimulate private-sector investment in technologies that enhance enterprise performance. Digital technologies and new digital services are expected to improve the performance of most sectors of the Greek economy; these expectations, together with the importance of the technology–organization–environment framework in the diffusion of innovations literature, suggest in a general sense that digitalization should also lead to improved economic performance in Greek enterprises [1]. Despite the growing prominence of digital technologies in enterprise strategies, their economic effects remain highly context dependent. Differences in institutional environments, market structures, and firm capabilities shape both the pace of adoption and the realization of performance gains. As a result, digitalization cannot be assumed to generate uniform outcomes across countries or industries. In economies characterized by a high prevalence of small and medium-sized enterprises, such as Greece, these contextual factors become particularly salient, influencing not only the feasibility of digital investments but also their capacity to translate into measurable productivity improvements. Furthermore, the diffusion of digital technologies often entails significant adjustment costs that may initially offset potential efficiency gains. Organizational restructuring, workforce training, and changes in managerial practices are frequently required before digital tools can be effectively integrated into core business processes. These transitional dynamics help explain why short-term performance effects may be weak or uneven, especially in firms with limited financial resources or low digital maturity. Consequently, evaluating the economic impact of digitalization requires attention not only to adoption levels but also to the depth and quality of technology use. At the policy level, digital transformation strategies increasingly emphasize the role of enterprises as key agents of economic modernization. In the Greek case, public initiatives aimed at accelerating digital uptake reflect broader objectives related to competitiveness, resilience, and structural upgrading. However, the effectiveness of such strategies depends on the alignment between policy instruments and firm-level constraints. Without complementary investments in skills development, organizational capabilities, and institutional support, digital technologies risk remaining underutilized, limiting their potential contribution to productivity growth. For conceptual clarity, the present study uses the term digital technologies to refer collectively to the principal technological systems examined in the analysis, including artificial intelligence applications, data analytics platforms, Internet of Things (IoT) sensor networks, cloud computing infrastructures, and digital platforms. Although these technologies differ in their operational functions and economic mechanisms, they jointly form the technological foundation of enterprise digital transformation. Maintaining consistent terminology throughout the analysis helps clarify the specific channels through which digital technologies influence organizational performance and productivity.

To avoid treating digitalization as a vague or homogeneous concept, this study adopts a technology-specific approach. The term digital technologies refers here to a set of distinct but complementary tools that differ in functionality, application processes, and economic effects. In particular, artificial intelligence (AI) systems are understood as enterprise-level applications based on machine learning algorithms, including predictive models, classification systems, and optimization routines used for forecasting, pricing, scheduling, and decision support. Data analytics technologies encompass business intelligence platforms, statistical and algorithmic data-processing tools, and real-time dashboards that transform operational and market data into actionable managerial insights. Internet of Things (IoT) technologies are defined as sensor network applications embedded in physical assets, production lines, logistics systems, and infrastructure, enabling continuous data collection, monitoring, and automated control. Cloud computing refers to scalable, on-demand computing and storage infrastructures that support the deployment and integration of AI, analytics, and enterprise software systems. Finally, digital platforms and e-commerce technologies include online sales channels, digital payment systems, and digital marketing tools that primarily affect firms' market access and demand-side performance. By distinguishing between these technologies, the analysis avoids generic references to "digital technology" and allows for a more precise examination of the channels through which digital transformation affects enterprise performance. By situating digital adoption within this broader economic and institutional context, the present analysis contributes to a more comprehensive understanding of digitalization as a multifaceted process. Rather than treating digital technologies as standalone productivity enhancers, it highlights their interaction with organizational, sectoral, and policy factors. This perspective provides a more realistic basis for assessing the conditions under which digital transformation can support sustainable economic performance in Greek enterprises. A clearer understanding of the economic effects of digital transformation requires distinguishing between the specific technologies that compose modern digital ecosystems within enterprises. Rather than viewing digitalization as a single technological input, it is necessary to consider the different systems responsible for data generation, processing, and decision support. These technologies perform distinct operational roles within firms and influence productivity through different economic mechanisms. The following discussion therefore introduces the main technological components examined in this study and explains how their functional characteristics shape enterprise performance.

The contribution of this study lies primarily in structured synthesis and mechanism-based interpretation rather than in methodological novelty. By distinguishing between technology types, deployment stages, and performance channels, and by organizing adoption evidence within a coherent theoretical–visual framework, the analysis advances understanding of how digital transformation operates in a structurally heterogeneous SME-dominated economy. The originality resides in integrating adoption patterns, productivity mechanisms, sectoral heterogeneity, and policy implications into a unified analytical architecture tailored to the Greek context. This synthesis-oriented contribution provides a structured roadmap for future empirical research employing richer micro-level data and formal econometric identification strategies.

Recent research highlights the importance of data openness and large-scale monitoring infrastructures in enabling AI-driven analytics systems. In modern digital environments, large volumes of data are generated by distributed sensors, digital platforms, and enterprise information systems. Open data ecosystems allow organizations and institutions to share and reuse datasets, which can be processed through machine learning algorithms to detect patterns, forecast trends, and improve operational decision-making. In smart city and digital infrastructure contexts, open data platforms support predictive models for traffic management, energy efficiency, environmental monitoring, and urban planning. Studies show that machine learning applications built on open data repositories significantly enhance the capacity of analytics systems to extract actionable insights from complex datasets and support real-time decision processes. IoT infrastructures enable continuous monitoring of physical processes and assets through networks of connected sensors that collect real-time operational data. These sensors measure variables such as temperature, energy consumption, machine vibration, traffic flows, or environmental conditions. The collected data are transmitted to analytics platforms where machine learning algorithms process them to identify anomalies, optimize system performance, and support predictive decision-making. Such monitoring systems are widely used in smart infrastructures and industrial environments because they allow organizations to detect operational inefficiencies and emerging failures before they cause significant disruptions. By integrating IoT sensing technologies with advanced analytics tools, organizations can transform raw operational data into actionable insights that improve efficiency and resource allocation. A particularly important application of IoT-enabled monitoring is predictive maintenance, where machine learning models analyze sensor data to predict equipment failures before they occur. Instead of relying on reactive or scheduled maintenance, predictive systems continuously evaluate equipment conditions and trigger maintenance actions when abnormal patterns are detected. This approach significantly reduces downtime, maintenance costs, and operational disruptions while improving system reliability and asset lifespan. In complex infrastructures such as smart cities, transportation systems, or industrial facilities, predictive maintenance allows managers to shift from reactive repair strategies to proactive, data-driven management of assets and resources. The integration of open data platforms, AI analytics, and IoT monitoring systems creates a digital ecosystem in which operational processes can be continuously analyzed and optimized. Data generated by sensors and digital platforms become inputs for machine learning algorithms that identify patterns, forecast system behavior, and guide automated or managerial decisions. This interaction between data generation, data openness, and algorithmic processing explains why digital technologies contribute to productivity improvements. When organizations combine monitoring technologies with analytics capabilities, they can enhance resource allocation, reduce operational inefficiencies, and support evidence-based decision-making across complex operational environments [2–4]. The integration of open data platforms, AI analytics, and IoT monitoring systems creates a digital ecosystem in which operational processes can be continuously analyzed and optimized. Data generated by sensors and digital platforms become inputs for machine learning algorithms that identify patterns, forecast system behavior, and guide automated or managerial decisions. This interaction between data generation, data openness, and algorithmic processing explains why digital technologies contribute to productivity improvements. When organizations combine monitoring technologies with analytics capabilities, they can enhance resource allocation, reduce operational inefficiencies, and support evidence-based decision-making across complex operational environments. Cloud computing has emerged as a fundamental enabling infrastructure for large-scale digital ecosystems because it provides scalable storage, distributed computing power, and on-demand access to advanced analytics tools. In smart city environments and digital infrastructures, cloud platforms support the integration of data generated by heterogeneous sources such as IoT sensors, public databases, enterprise systems, and communication networks. Through centralized and distributed processing architectures, cloud systems enable real-time analytics, data sharing, and large-scale monitoring applications. These infrastructures support complex data processing tasks, including traffic optimization, environmental monitoring, healthcare analytics, and energy management. As a result, cloud computing functions as a core technological backbone that allows organizations to process large volumes of operational data and transform them into actionable insights for decision-making and system optimization. The integration of cloud computing with Internet of Things (IoT) infrastructures enables continuous monitoring of physical systems through distributed sensor networks. IoT devices collect real-time data from operational environments such as industrial equipment, transportation systems, or urban infrastructure. These data streams are transmitted to cloud platforms where they are aggregated, processed, and analyzed using advanced analytics algorithms and machine learning techniques. Such architectures allow organizations to monitor operational conditions in real time, detect anomalies, and improve system performance through predictive and automated responses. By combining large-scale cloud analytics with sensor-based data acquisition, digital infrastructures can support data-driven management strategies that improve operational efficiency and resource allocation. Cloud-based analytics platforms also facilitate advanced predictive models that support operational optimization and predictive maintenance. In many digital infrastructures, machine learning algorithms analyze large datasets collected from sensors and enterprise information systems to identify patterns, forecast system behavior, and anticipate potential failures. These predictive capabilities allow organizations to shift from reactive management approaches to proactive decision-making strategies based on real-time data insights. In smart infrastructure environments, such systems can improve the reliability of transportation networks, energy systems, and industrial operations while reducing maintenance costs and operational disruptions. Consequently, the integration of cloud computing, IoT sensing technologies, and advanced analytics creates a data-driven ecosystem that enhances monitoring capacity and supports continuous performance improvement. The interaction between cloud computing, IoT monitoring systems, and advanced analytics technologies explains why digital infrastructures are increasingly associated with productivity improvements. When organizations integrate cloud platforms with sensor networks and machine learning algorithms, they create digital ecosystems capable of transforming raw operational data into actionable knowledge. These systems enable real-time monitoring, predictive maintenance, and automated optimization of operational processes, which collectively improve efficiency, reduce downtime, and enhance resource allocation. Therefore, cloud-based digital infrastructures function not only as data storage environments but also as analytical platforms that support intelligent decision-making and continuous performance improvement across complex operational systems [2–4].

2. Literature Review and Methodology

A sizable body of literature investigates the relationship between digital technologies and the economic performance of enterprises. Recent studies also emphasize the role of large-scale digital infrastructures and open data ecosystems in enabling advanced monitoring and analytics capabilities. Cloud computing platforms provide scalable processing environments that support the integration of data generated by distributed Internet of Things (IoT) sensor networks, enterprise systems, and public data repositories. Within such digital environments, machine learning algorithms can process large volumes of real-time information to detect operational patterns, identify anomalies, and support predictive decision-making. Research on smart infrastructure and digital urban systems demonstrates that cloud-based analytics platforms combined with open data architectures significantly enhance monitoring capacity and operational efficiency in complex digital ecosystems. These findings reinforce the view that the productivity effects of digital technologies emerge not only from isolated technological adoption but also from the integration of data generation, data processing, and analytical capabilities within interconnected digital infrastructures. This dimension of the economic literature also offers specific results for Greece. However, the academic and policy interest in the adoption of digital technologies by Greek enterprises has so far outpaced research in this area, as noted in the introduction. Therefore, irrefutable evidence of the impact of digitalization on Greek enterprises has not yet been firmly established. The empirical study fills this gap. Existing empirical findings on the economic effects of digital technologies remain fragmented, largely because studies differ in their definitions of digitalization, methodological approaches, and performance metrics. While some analyses emphasize information and communication technologies as a homogeneous category, others focus on specific tools or applications, making cross-study comparison difficult. This heterogeneity has contributed to mixed and sometimes contradictory conclusions regarding the magnitude and direction of digitalization's impact on firm performance. In the Greek context, the available evidence is particularly limited and often confined to narrow sectors or single technologies. As a result, important dimensions of digital transformation—such as the interaction between multiple technologies, the role of organizational capabilities, and the timing of performance effects—remain underexplored. Moreover, much of the existing work relies on descriptive statistics or partial indicators, offering limited insight into productivity dynamics and growth mechanisms at the firm level. The present study advances literature by adopting a broader and more integrated perspective on digital adoption. Rather than examining individual technologies in isolation, it considers a portfolio of digital tools and evaluates their combined and differentiated effects on economic performance. This approach allows for a clearer distinction between technologies that primarily influence market outcomes, such as sales and output growth, and those that reshape internal production processes and efficiency [5,6]. By linking adoption patterns to multiple measures of productivity and growth, the analysis contributes to a more nuanced understanding of how digital technologies operate as drivers of economic performance. In doing so, it responds directly to the need for systematic and context-specific evidence, offering insights that are relevant not only for academic research but also for policy design and strategic decision-making within enterprises. First, available sources shed light on the level of adoption of digital technologies, their penetration in different sectors, and the barriers that hinder faster adoption. Next, the impact of digitalization on productivity and economic growth is examined [7–11]. Numerous studies test the link between the use of digital technologies or, more broadly, of information and communication technologies (ICTs) and the performance of firms [12–16]. Most find a positive correlation—supported in some cases by causality tests—although a number of studies employing rigorous econometric techniques detect no such link [17–19]. Different types of labor productivity, total factor productivity (TFP), and sales growth constitute the main performance metrics used in these analyses [20–24]. Beyond documenting adoption levels, recent research emphasizes that the economic effects of digital technologies depend critically on how such technologies are integrated into firms' production and organizational structures. Digital tools that merely automate existing processes often generate limited gains, whereas technologies embedded within broader organizational change tend to yield more substantial productivity improvements. This distinction helps explain why empirical findings vary across studies, even when similar technologies are examined. The literature further indicates that productivity outcomes differ according to the type of performance indicator employed. Measures such as labor productivity may capture short-term efficiency gains linked to workforce reorganization or cost reductions, while total factor productivity reflects deeper structural changes in the use of capital, labor, and technology [1,25]. Consequently, studies rely on a single productivity metric, risk underestimating or misinterpreting the broader impact of digitalization. A multi-dimensional approach to performance measurement is therefore essential for a comprehensive assessment. Another strand of the literature highlights the importance of timing in evaluating the effects of digital adoption. The benefits of digital investments often materialize with a delay, as firms require time to accumulate experience, adapt workflows, and develop complementary skills [26,27]. At the same time, firm heterogeneity plays a central role in shaping observed outcomes. Larger firms and those operating in knowledge-intensive sectors generally possess greater absorptive capacity, enabling them to leverage digital technologies more effectively. In contrast, small and medium-sized enterprises frequently face financial, organizational, and skills-related constraints that limit the scale and effectiveness of digital investments. These differences contribute to uneven performance effects both within and across sectors. Empirical studies also suggest that the relationship between digitalization and growth is not strictly linear. Incremental adoption of isolated technologies may yield modest gains, whereas the combination of multiple digital tools can generate complementarities that amplify performance effects. Such synergies underline the importance of viewing digital transformation as a cumulative and systemic process rather than as a sequence of independent technological choices. In the context of Greece, these insights underscore the need for analyses that go beyond aggregate indicators and examine firm-level and sector-specific dynamics. Given the structural characteristics of the Greek economy, including the dominance of SMEs and the prevalence of traditional sectors, understanding the channels through which digital technologies affect productivity and growth is particularly important. reinforces the relevance of policy-oriented research [28,29]. If digital technologies do not automatically translate into improved performance, public interventions must be carefully designed to support not only adoption but also effective utilization. Empirical studies that integrate adoption patterns, performance outcomes, and contextual constraints provide valuable guidance for shaping policies that enhance the productivity and growth effects of digital transformation. It is important to clarify that the present research is grounded primarily in theoretical analysis and structured visualization, rather than in large-scale econometric estimation based on longitudinal microdata. The methodological design builds on established economic theories of productivity, innovation diffusion, and organizational change, using visualization techniques to synthesize complex relationships between digital adoption and economic performance. This approach allows the study to integrate diverse dimensions—technological, organizational, sectoral, and institutional—within a coherent analytical framework. Understanding how digital technologies influence enterprise productivity requires situating the analysis within the broader academic literature on digital transformation and firm performance. Previous research has explored the economic implications of information technologies, artificial intelligence systems, and data-driven infrastructures across a wide range of sectors and institutional environments. However, empirical findings remain heterogeneous due to differences in technological definitions, measurement approaches, and country-specific structural conditions. The following section therefore reviews the relevant literature and presents the methodological framework used to examine the relationship between digital technology adoption and economic performance in Greek enterprises.

Visual representations, including conceptual diagrams and heatmap-based illustrations, are employed as analytical tools rather than as descriptive add-ons. These visualizations serve to summarize multidimensional relationships that are difficult to capture through single regression coefficients alone, such as the differentiated effects of digital technologies across performance indicators and sectors. By translating theoretical relationships into structured visual forms, the analysis enhances interpretability and facilitates comparison across technologies and performance dimensions. The reliance on theory and visualization is particularly appropriate in contexts where data limitations constrain the use of fully specified econometric models. In the Greek case, gaps in longitudinal firm-level data and inconsistencies in technology-specific measurement limit the feasibility of causal estimation at scale. Under such conditions, theory-driven visual analysis provides a rigorous alternative for identifying patterns, mechanisms, and plausible economic channels through which digital transformation affects enterprise performance. Moreover, the visualization-based approach supports policy relevance and strategic insight. Policymakers and business decision-makers often require integrative representations that link technology adoption to productivity, growth, and structural change. The theoretical–visual framework adopted in this study enables the identification of priority technologies, sector-specific dynamics, and complementarities among digital tools, offering actionable insights without overstating causal claims. In this sense, the study should be understood as analytical and explanatory rather than predictive. Its contribution lies in clarifying mechanisms, highlighting heterogeneity, and organizing existing empirical and theoretical knowledge into a structured framework that can guide future empirical research. Subsequent studies may build on this foundation by incorporating richer datasets and formal econometric testing, using the visual and theoretical insights developed here as a roadmap for hypothesis formulation and empirical validation.

Figure 1 presents a comprehensive methodological framework that explains how the study links digital technology adoption to economic performance in Greek enterprises. It is structured as a top-down analytical process, starting from the research objective and data sources and progressing through variable construction, empirical analysis, and policy-relevant outcomes. At the top of the diagram, the research aim is clearly defined as examining the relationship between digital adoption and economic performance. This is followed by the data sources, which consist of enterprise-level surveys and complementary policy data. These sources provide the empirical foundation for the entire analysis. The next stage introduces the core variables of the study. Digital adoption is captured through three dimensions of technology, intensity of use, and timing of adoption—reflecting both the breadth and depth of digitalization. Economic performance is measured using output, sales, labor productivity, and total factor productivity (TFP), allowing the analysis to capture both short-term growth effects and deeper efficiency changes. A set of control variables—including sector, firm size, region, skills, and financial capacity—accounts for structural heterogeneity across enterprises. Following variable construction, the framework proceeds to descriptive analysis, which serves as a diagnostic stage. Here, the study documents adoption and diffusion patterns across technologies and sectors and identifies the drivers and barriers shaping digital transformation. To improve accessibility and interpretability, the conceptual figures presented in this study are intended as structured visual summaries rather than technical diagrams. In particular, **Figure 1** should be read as a logical flow representation of the analytical process rather than as a fully specified econometric model. Arrows denote conceptual relationships and estimation stages rather than strict causal pathways. Similarly, the heatmap and schematic diagrams use graded intensity scales to illustrate relative strength of associations rather than precise coefficient magnitudes. This clarification ensures that non-specialist readers interpret the figures as explanatory tools that synthesize multidimensional relationships rather than as formal statistical models.

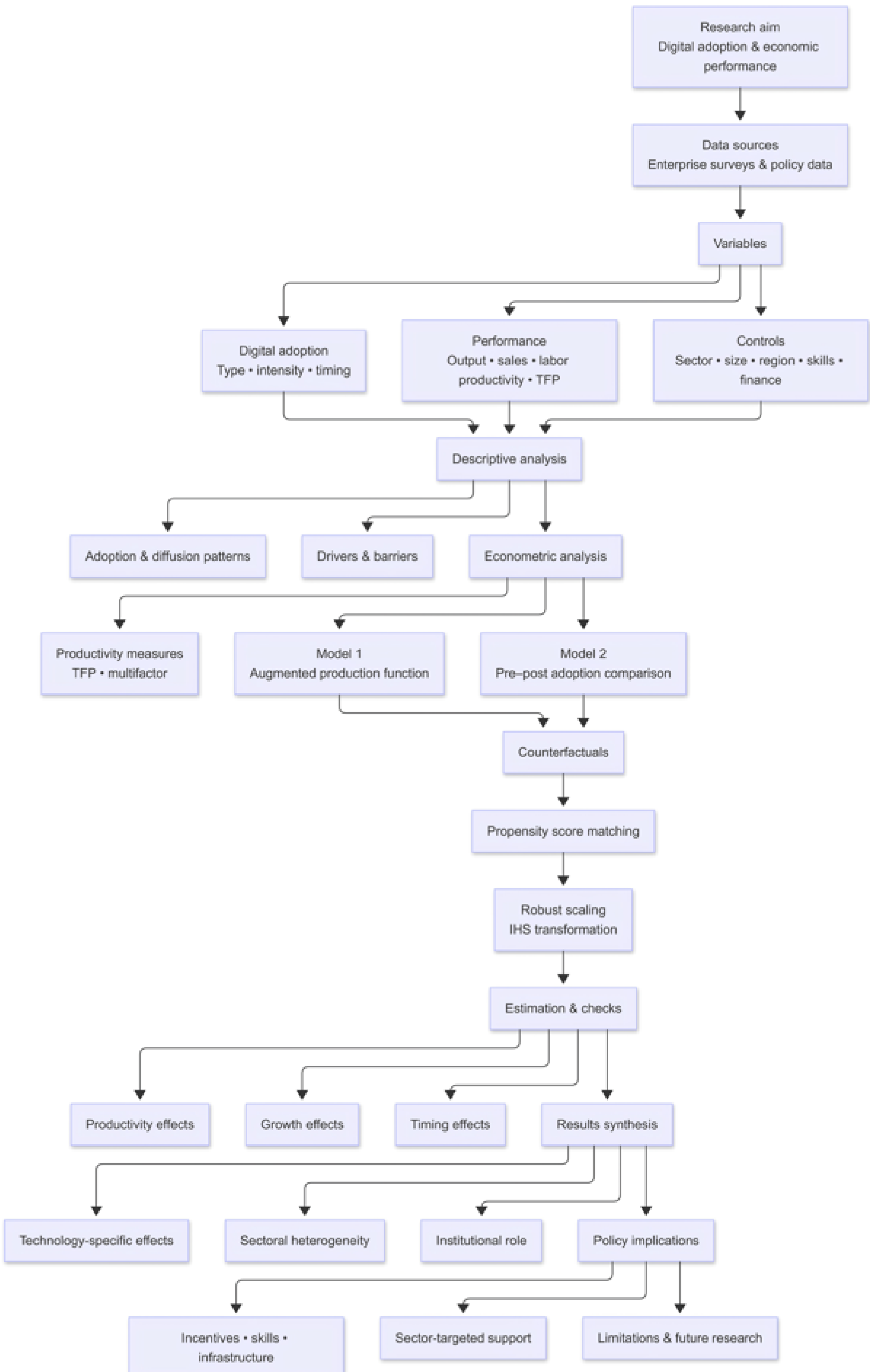

Figure 1. Economic Performance of Greek Enterprises Based on Digital Technologies.

Figure 1 should be interpreted as a theory-driven identification framework that connects enterprise-level digital technology adoption to economic performance through well-established mechanisms from productivity theory and the economics of innovation. The conceptual foundation is consistent with the technology–organization–environment (TOE) framework and diffusion-of-innovation logic: adoption depends not only on technology availability but also on organizational readiness (skills, managerial capacity, governance structures) and environmental conditions (sectoral competition, regulation, financing constraints). In the Greek context—where SMEs dominate and capability dispersion is substantial—these theoretical considerations are especially relevant, because adoption decisions are shaped by heterogeneous absorptive capacity and by constraints in finance and human capital. Consequently, **Figure 1** treats adoption as an endogenous firm decision that must be interpreted jointly with controls capturing firm structure and operating environment. The first model in **Figure 1** ("Augmented production function") is grounded in standard productivity theory: enterprise output is produced using labor and capital, and technology affects output either by shifting the production frontier (total factor productivity improvements) or by improving the efficiency with which inputs are combined. Digital technologies—particularly ERP, BI, analytics, AI, IoT, and cloud infrastructures—are treated as productivity-enhancing factors because they reduce coordination costs, improve information quality, and strengthen resource allocation efficiency. The production-function augmentation reflects the idea that digital adoption acts as an organizational and informational capital input that can raise productivity beyond what is explained by conventional inputs alone. This mechanism is consistent with the general-purpose technology (GPT) view of digital infrastructures (especially cloud and data platforms), where performance effects are amplified when complementary investments (skills, organizational restructuring, process redesign) are present. For Greece, this framing is important because it explains why adoption effects are expected to be heterogeneous across sectors and firm sizes and why the strongest gains are typically observed when digital technologies are integrated rather than adopted in isolation. The second model in **Figure 1** ("Pre–post adoption comparison") is motivated by the timing and learning dimensions of digital transformation. A central theoretical point is that digital technologies often yield delayed returns: firms require time to integrate systems into workflows, train personnel, restructure processes, and exploit complementarities among technologies. A pre–post design is therefore introduced to capture dynamic adjustment and to reduce concerns that higher performance simply precedes adoption (reverse causality). In practical terms, comparing performance trajectories before and after adoption provides evidence that is more consistent with a technology-to-performance mechanism, particularly when pre-adoption trends are weak or negative and post-adoption trajectories improve. In the Greek case—where digital diffusion was accelerated during and after the pandemic and where policy instruments reduced adoption costs—timing effects are especially salient, because adoption may reflect both structural upgrading and short-term response to shocks. The pre–post logic helps distinguish immediate "diffusion" effects from medium-term "integration" effects. Because both model paths face a common challenge—non-random selection into adoption—**Figure 1** explicitly introduces a counterfactual framework, implemented through propensity score matching. The theoretical purpose of matching is to approximate the comparison that would be observed if adopting firms could be compared to non-adopting firms with similar observable characteristics (sector, size, region, skills, finance). This step reflects the core econometric principle that adopters typically differ from non-adopters in systematic ways, and these differences may independently explain performance gaps. By constructing a matched control group, the analysis reduces selection bias and strengthens interpretive credibility, while remaining consistent with the manuscript's overall emphasis on structured, theory-guided inference rather than full-scale causal identification. **Figure 1** also includes robust scaling and the inverse hyperbolic sine transformation to address empirical features that are common in enterprise performance data, particularly in Greece: skewed distributions, heteroskedasticity, and the presence of zeros or extreme values in variables related to output, productivity proxies, or investment measures. The role of this step is not purely technical; it supports the broader methodological objective of ensuring that observed relationships are not driven by outliers or distributional artifacts. In combination with estimation checks, this contributes to internal validity and improves comparability across sectors with very different firm structures and performance distributions. The lower part of **Figure 1** organizes results into four interpretable categories—productivity effects, growth effects, timing effects, and synthesis—because the underlying theory predicts differentiated outcomes depending on the functional orientation of each technology. Market-facing technologies (e-commerce, digital platforms, social media marketing) are expected to influence performance primarily through demand expansion, market access, and transaction cost reductions, which should be visible in sales and output growth. In contrast, production- and decision-oriented technologies (ERP, BI, analytics, AI, IoT, cloud) are expected to operate through internal efficiency mechanisms and organizational learning, which should be more strongly associated with labor productivity and total factor productivity. This structured mapping is essential for policy relevance: it clarifies why instruments aimed only at increasing "adoption rates" may be insufficient if they do not also support complementary investments (skills, governance, integration capability) required for productivity effects to materialize in Greek enterprises.

From an econometric perspective, the boxplot provides a non-parametric distributional assessment of enterprise digital adoption across EU countries, complementing the tabulated evidence in **Tables 1** and **2**. Rather than estimating a conditional mean effect through regression coefficients, the boxplot summarizes the unconditional distribution of the key digital adoption indicator, allowing for an assessment of central tendency, dispersion, and relative positioning without imposing functional form assumptions. The location of Greece slightly above the EU median indicates that its observed adoption level is not driven by extreme values or outliers, but lies within the upper half of the empirical distribution. This supports the robustness of the comparative conclusions drawn from **Table 2** and reduces concerns that the observed differences are artefacts of skewness or measurement noise. In applied econometric terms, the figure suggests that Greece's digital adoption performance is statistically plausible within the European distribution and consistent with a shift in the distribution's upper quantiles rather than a marginal fluctuation around the mean. While the boxplot does not test causality, it provides distributional validation for the economic significance of the observed differences, reinforcing the interpretation that enterprise digitalization in Greece represents a structural rather than incidental phenomenon.

Table 1. Adoption of Enterprise Business Software in Greece (2023–2025) [30].

Country	2023	2025	Change (pp)	Growth (%)
Greece (EL)	49.07	57.05	7.98	16.26

Table 2. Comparative Adoption of Enterprise Business Software: Greece and EU-27 (2025) [30].

Country/Region	2025	Difference vs. Greece (pp)
Greece (EL)	57.05	—
EU-27 average	53.47	−3.58

3. Digital Technologies in Greek Enterprises: Adoption and Diffusion

The adoption of digital technologies by Greek enterprises exhibits substantial variation not only in intensity but also in technology type and application purpose. Market-facing technologies—such as e-commerce platforms and social media marketing tools—are primarily deployed to expand customer reach, facilitate transactions, and support sales growth. These technologies are typically easier to adopt and require limited organizational restructuring, which partly explains their relatively higher diffusion rates across sectors. In contrast, data-intensive and production-oriented technologies—including AI systems, machine learning–based analytics, IoT sensor applications, and cloud-based infrastructures—remain at earlier stages of diffusion. AI adoption in Greek enterprises is largely concentrated in forecasting, customer analytics, and process optimization applications, while IoT usage is mainly associated with monitoring, logistics tracking, and maintenance-related functions. Data analytics tools are increasingly used to support managerial decision-making, but their effectiveness depends heavily on data availability, workforce skills, and organizational readiness. Cloud computing plays a supporting role by reducing fixed IT costs and enabling access to advanced computational capabilities, particularly for small and medium-sized enterprises. These differences indicate that observed adoption patterns reflect not only financial constraints but also the complexity of technology implementation and integration. Technologies that require organizational change, skill upgrading, and process redesign diffuse more slowly but are more closely associated with productivity and efficiency improvements. Recognizing these distinctions is essential for interpreting the heterogeneous performance effects of digitalization across sectors and firm types.

Greek enterprises employ various digital technologies with varying penetration rates. Internet-based systems for banking and financial transactions and social media for marketing have the widest diffusion, followed by e-commerce. Given the COVID-19 pandemic, it is no surprise that video conferencing and collaboration tools, virtual private network technological solutions, and teleworking technologies are also utilized by a significant proportion of enterprises. Nevertheless, cloud services and Internet of Things (IoT) technologies have a much lower penetration, and Artificial Intelligence systems and advanced data analytics systems remain in their infancy. Adoption levels in Northern Greece are significantly lower than in the South. The adoption process includes all stages, from awareness to planning, procurement, and full utilization, although most enterprises have already made the investment. Diffusion across sectors shows differences attributable to enterprise size, with manufacturing leading and construction lagging behind. Telecommunications is characterized by the speed of diffusion across all sizes, while hospitality (part of the tourism sector) is behind in adoption [31–35]. The most significant drivers of adoption are personnel-digital skills, financial capital, enterprise age, and participation in enterprise collaborating networks, while the most important inhibitors are financial constraints and the absence of a digital-ready culture [36–39]. The diverse portfolio of digital technologies used by Greek enterprises is or should be increasingly driving their productivity and growth performance. A detailed examination of the productivity–digitalization nexus includes estimation of the economic according to alternative productivity definitions (total factor productivity, output per unit of capital, and multifactor productivity), followed by analysis of growth according to two different approaches. The first derives from the estimation of a production function augmented with digital adoption by means of a relative-time variable by sector; it provides evidence of the average productivity boost triggered by digital adoption. The second approach compares post-adoption performance with that realized in the years preceding the investment. These estimations, where the identified relationship is controlled by an inverse hyperbolic sine transformation of the nondigital variables, are implemented by means of a propensity match technique in order to derive a proper counterfactual for the performance of adopters in the absence of investment [8,13,16,40–44].

Digital technologies influence enterprise performance through distinct application mechanisms, depending on their functional orientation and mode of use within the firm. Understanding these mechanisms is essential for explaining why different technologies generate different economic outcomes. Artificial intelligence systems, implemented through machine learning algorithms, operate primarily as decision-enhancing and automation tools. By processing large volumes of data, AI applications improve forecasting accuracy, optimize resource allocation, and reduce coordination costs. Their economic impact materializes mainly through gains in labor productivity and total factor productivity, as firms achieve higher output with the same or fewer inputs. Data analytics technologies function as decision-support systems that translate operational, financial, and market data into structured information. Their primary mechanism is improved managerial decision-making, enabling firms to identify inefficiencies, adjust strategies in real time, and allocate resources more effectively. Productivity gains arise from better utilization of existing capital and labor rather than from scale expansion. Internet of Things applications rely on sensor networks that continuously monitor physical processes, assets, and logistics flows. These systems enable predictive maintenance, reduce downtime, and improve input efficiency. The resulting performance effects are typically indirect and medium-term, contributing more strongly to efficiency and TFP improvements than to immediate sales growth. Cloud computing serves as a general-purpose enabling infrastructure that supports the deployment, integration, and scalability of other digital technologies. Its economic role is largely complementary: cloud adoption amplifies the productivity effects of AI, analytics, and IoT by lowering entry barriers, improving interoperability, and enhancing organizational flexibility. Digital platforms and e-commerce systems affect performance primarily through demand-side mechanisms. By expanding market access, reducing transaction costs, and improving customer matching, these technologies generate output and sales growth without fundamentally altering production processes. Their contribution to productivity is therefore more limited and indirect. Digital transformation enhances enterprise performance not through isolated technology adoption, but through the integration of multiple technologies into coherent operational systems. The strongest economic effects emerge when firms combine data generation (IoT), data processing (analytics and AI), infrastructure support (cloud computing), and market access (digital platforms), allowing complementarities and learning effects to materialize.

An important analytical distinction concerns the stage of deployment of advanced digital technologies, particularly in small and medium-sized enterprises. In the Greek context, adoption of AI, analytics, and IoT systems often occurs at varying levels of maturity. Experimental deployment refers to pilot or limited-scope applications, typically confined to isolated functions such as forecasting, customer analytics, or equipment monitoring, without full integration into enterprise-wide workflows. Partial deployment describes technologies that are functionally integrated within selected departments—such as predictive maintenance modules in manufacturing or analytics dashboards in retail—yet remain disconnected from broader organizational decision structures. Mature deployment, by contrast, involves cross-departmental integration, interoperability with ERP systems, automated data flows, and systematic use in managerial decision-making. This differentiation is particularly relevant for SMEs, where financial and managerial constraints often limit integration depth. Consequently, reported adoption rates may overstate the extent of structural digital transformation if deployment maturity is not considered. Productivity effects are more plausibly associated with mature integration than with experimental or partial implementation. Recognizing these stages clarifies why observed performance gains may vary across firms despite similar nominal adoption indicators and strengthens interpretation of heterogeneous digital impact in the Greek economy.

4. Empirical Evidence on Productivity and Growth

Are productivity and growth positively associated with the adoption of digital technologies by Greek enterprises? Statistics suggest that productivity and growth performance are positively related to the level of digital adoption, with some variation across sectors. Digital technologies are observed to have greater impact on output of enterprises in a majority of the sectors, followed by total factor productivity (TFP) and multifactor productivity. The comparison of performance levels—TFP, product, multifactor productivity—between enterprises that have adopted a technology and their counterparts that have not adopted the technology confirms these conclusions. Analysis of the effect of digitalization on growth, using TFP and output growth rates as dependent variables, shows that higher levels of digital uptake, measured as the number of digital technologies adopted, are positively related to both TFP and output growth rates. Formal tests of the relationship between growth and digital uptake also confirm the important role that digitalization plays in growth. Further insights emerge from examining the timing of the relationship between growth and digitalization. One framework suggests that it is possible to observe the effect of digital investment on business performance only sometime after such investment, as the benefits build up over time. Therefore, the comparison of the performance of the same enterprises before and after digital adoption can provide a clearer view of their growth impact. Such tests, undertaken for a number of major digital technologies, indicate that output and TFP growth rates are significantly higher after the adoption of the relevant technology and, in some cases, that the growth rates before digitalization were negative. This later-stage analysis is important, as under such conditions the potential causal direction of growth leading to digital investment becomes a less serious concern [38,45–47].

The empirical analysis in this chapter is based on enterprise-level data derived from the harmonized Eurostat survey on ICT usage in enterprises [48–50]. The survey applies a stratified sampling design to ensure representativeness across firm size classes, economic sectors, and geographical regions. The effective sample consists of enterprises for which complete information on digital technology adoption indicators is available, allowing consistent temporal and cross-country comparison. This sampling framework supports the identification of structural patterns in digital adoption while avoiding biases associated with sectoral or size concentration. Digital technology adoption is measured using quantitative survey indicators capturing the use of core enterprise business software, namely Enterprise Resource Planning (ERP), Customer Relationship Management (CRM), and Business Intelligence (BI) systems. These technologies are treated as a unified indicator of internal, data-driven digitalization, as they represent the organizational backbone for data integration, analytics, and decision-support processes. Adoption intensity is expressed as the percentage of enterprises reporting the use of at least one such system, providing a transparent and comparable measure of digital transformation across firms and over time.

Table 1 reports the evolution of business software adoption among Greek enterprises between 2023 and 2025. The results reveal a pronounced increase in internal digitalization, with the share of enterprises using ERP, CRM, or BI systems rising from 49.1% in 2023 to 57.1% in 2025. This corresponds to an increase of nearly eight percentage points, or a relative growth rate of approximately 16%. Such a change is economically meaningful and indicates an accelerated diffusion of data-driven management systems within a short time horizon. Given the role of these systems in integrating operational data and supporting analytics-based decision-making, the observed increase reflects a strengthening of firms' internal digital capabilities rather than superficial or symbolic digital adoption.

To contextualize this trend, a comparative perspective is provided:

Table 2 compares Greece with the EU-27 average in 2025 with respect to the adoption of enterprise business software. The results show that Greece slightly exceeds the EU-27 average by approximately 3.6% points. This finding is noteworthy given the structural characteristics of the Greek economy, including the high prevalence of small and medium-sized enterprises, which typically face greater constraints in adopting complex digital systems. The evidence suggests that Greek enterprises have achieved a level of internal digital infrastructure that is broadly comparable to, and in this case marginally stronger than, the European average.

Figure 2 presents the distribution of enterprise business software adoption across EU Member States in 2025, measured as the share of enterprises using Enterprise Resource Planning (ERP), Customer Relationship Management (CRM), or Business Intelligence (BI) systems. The boxplot summarizes cross-country variation by depicting the median adoption rate, the interquartile range, and the overall dispersion across the European Union. This visualization provides a compact representation of heterogeneity in internal digitalization among European enterprises. The median adoption level lies slightly above 50%, indicating that in a typical EU country roughly half of enterprises have integrated at least one core business software system into their operations. The interquartile range, spanning approximately from the mid-30% to the high-50% range, highlights substantial variation in digital adoption intensity across countries. This dispersion reflects differences in firm structure, digital readiness, institutional frameworks, and access to complementary resources such as skills and finance. The upper range of the distribution, extending above 70%, suggests that in several countries enterprise business software adoption has reached a relatively advanced stage. Positioned within this distribution, Greece's adoption level, as reported in **Table 2**, lies slightly above the EU median. This placement indicates that Greek enterprises are not outliers, but rather occupy a relatively favorable position within the European landscape of internal digitalization. The visual evidence therefore complements the tabulated results by situating Greece's performance within the broader EU context and confirming that the observed adoption levels are economically meaningful rather than marginal. From an analytical perspective, the boxplot underscores that digital transformation in enterprises is uneven across Europe and cannot be treated as a uniform process. Since ERP, CRM, and BI systems primarily affect firm performance through internal organizational and efficiency-enhancing mechanisms, the observed cross-country dispersion implies corresponding heterogeneity in productivity-related digital capabilities. Consequently, the figure reinforces the interpretation that measurable differences in digital adoption are likely to translate into differentiated economic outcomes, supporting the study's broader conclusions on the role of internal digital technologies in shaping enterprise performance.

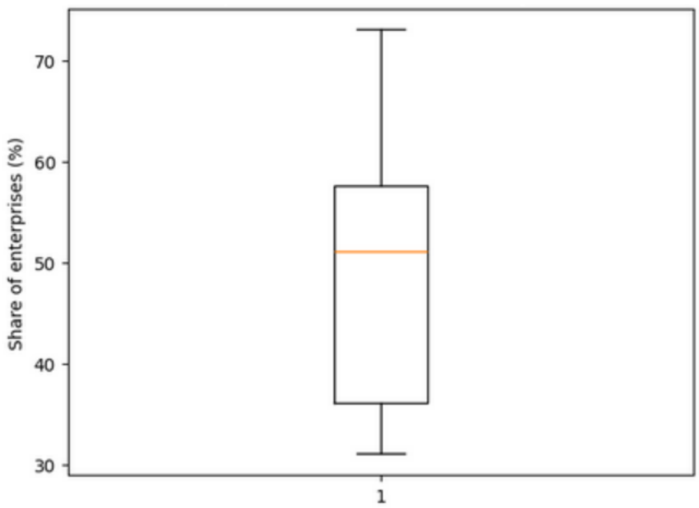

Figure 2. Distribution of Enterprises Business Software Adoption in the EU (See **Appendix A**).

From a quantitative standpoint, the magnitude and direction of change documented in **Tables 1** and **2** support economically significant conclusions. Although the analysis relies primarily on descriptive and comparative statistics rather than full-scale micro-econometric estimation, changes of this scale in harmonized enterprise indicators are widely interpreted in applied economic research as meaningful, particularly when they occur over a short period and align with broader structural transformation processes. The observed increase and cross-country positioning therefore provide strong indicative evidence of a positive digitalization trend. The economic relevance of these findings is closely linked to the productivity-oriented nature of the technologies examined. ERP, CRM, and BI systems primarily influence firm performance through internal organizational mechanisms, including process integration, information flow optimization, and improved resource allocation. As a result, their diffusion is more plausibly associated with productivity and total factor productivity improvements than with immediate demand expansion. The empirical patterns observed in **Tables 1** and **2** are therefore consistent with the study's broader interpretation that digital technologies affect enterprise performance mainly through efficiency-enhancing and structural channels. Illustrative enterprise-level evidence further clarifies these mechanisms. In manufacturing enterprises, ERP systems have been used to synchronize production planning, inventory management, and procurement, reducing idle capital and improving capacity utilization. When combined with BI tools, firms are able to monitor performance indicators in real time and adjust production schedules more efficiently. In service-sector enterprises, CRM and BI systems facilitate systematic analysis of customer data, enabling more targeted service provision and improved labor allocation. These application cases demonstrate how the technologies captured by the survey indicators translate into concrete operational improvements, reinforcing the quantitative evidence presented in the tables.

The evidence presented in this chapter demonstrates that digital technology adoption among Greek enterprises is not only measurable but also economically substantive. The sustained increase in the use of core enterprise business software systems, combined with Greece's favorable position relative to the EU average, indicates a structural strengthening of internal digital capabilities rather than a temporary or superficial adjustment. These technologies—encompassing enterprise resource planning, customer relationship management, and business intelligence systems—are closely linked to productivity-enhancing mechanisms, as they support data integration, analytics-based decision-making, and organizational coordination. Their diffusion therefore reflects a deeper transformation of firm-level operational and managerial processes. Importantly, digital transformation emerges from the analysis as a concrete and cumulative organizational process, driven by identifiable technologies that operate through well-defined economic channels. Rather than representing an abstract or uniform phenomenon, digitalization in Greek enterprises materializes through the progressive integration of data-driven systems into core business functions, enabling efficiency gains, improved resource allocation, and enhanced absorptive capacity for more advanced technologies. This interpretation provides a robust empirical foundation for the study's conclusions, reinforcing the view that digital technologies contribute meaningfully to enterprise performance when embedded within organizational structures and strategic processes, and not merely through nominal or isolated adoption.

In order to measure the level of digital transformation in Greece, it is important to look into similar parameters among other countries in Europe. The rates of enterprise business software adoption in some European economies in 2023 and 2025 are provided in **Table 3** below along with the respective percentage point differences and growth rate calculations. Such an assessment gives a more general understanding of where Greece stands among other nations in Europe in regard to digital technology adoption.

Table 3. Enterprise Business Software Adoption across European Countries (2023–2025).

Code	Country	2023	2025	Change (pp)	Growth (%)
DK	Denmark	73.59	73.07	−0.52	−0.7
FI	Finland	70.79	72.99	2.2	3.1
BE	Belgium	67.04	69.7	2.66	4
NL	Netherlands	67.7	69.56	1.86	2.7
ES	Spain	59.65	66	6.35	10.6
FR	France	53.76	60.15	6.39	11.9
LU	Luxembourg	53.7	58.8	5.1	9.5
MT	Malta	57.82	58.19	0.37	0.6
EL	Greece	49.07	57.05	7.98	16.3
IT	Italy	48.67	56.03	7.36	15.1
CZ	Czechia	34.22	54.25	20.03	58.5
PT	Portugal	52.63	53.68	1.05	2
EU27_2020	European Union (EU-27)	50	53.47	3.47	6.9
ME	Montenegro	53.66	53.17	−0.49	−0.9
NO	Norway	53.46	51.51	−1.95	−3.6
DE	Germany	51.27	51.37	0.1	0.2
CY	Cyprus	51.22	51.09	−0.13	−0.3
LT	Lithuania	45.38	50.01	4.63	10.2
IE	Ireland	46.13	47.19	1.06	2.3
AT	Austria	49.62	46.94	−2.68	−5.4
EE	Estonia	38.66	43.61	4.95	12.8
PL	Poland	38.88	41.8	2.92	7.5
SI	Slovenia	41.61	40.42	−1.19	−2.9
HU	Hungary	39.88	36.12	−3.76	−9.4
LV	Latvia	35.87	35.99	0.12	0.3
HR	Croatia	34.22	34.61	0.39	1.1

Table 3. *Cont.*

Code	Country	2023	2025	Change (pp)	Growth (%)
SK	Slovakia	32.09	33.57	1.48	4.6
RS	Serbia	26.22	33.38	7.16	27.3
BA	Bosnia and Herzegovina	27.23	32.79	5.56	20.4
RO	Romania	24.27	31.58	7.31	30.1
BG	Bulgaria	26.11	31.05	4.94	18.9
TR	Türkiye	32.48	31.05	−1.43	−4.4

As can be seen in **Table 3**, there is considerable variation in the adoption rate of enterprise business software solutions in Europe. The Nordic countries of Denmark, Finland, Belgium, and the Netherlands represent the top adopters of such software, owing to their developed digital environment. In Greece, one of the most improved performances is noted between 2023 and 2025, where the rate grows from 49.07% in 2023 to 57.05% in 2025, indicating an impressive growth rate of 16.3%, much higher than the EU-27 growth rate of 6.9%. Despite being below the digital front-runners of Europe in absolute terms, the fast-growing adoption rate shows clear convergence.

Figure 3 situates Greece within the broader European distribution of enterprise business software adoption, measured as the share of enterprises using ERP, CRM, or Business Intelligence systems. The boxplot illustrates cross-country dispersion, median positioning, and the relative concentration of adoption intensity across Member States. Greece's placement slightly above the EU median confirms that its internal digitalization level is structurally aligned with, and marginally stronger than, the European average. This positioning is economically significant given the structural characteristics of the Greek economy, which is dominated by small and medium-sized enterprises that traditionally face greater financial and organizational constraints in adopting complex digital systems. However, the cross-sectional nature of this distribution limits the ability to establish strong causal inference regarding the relationship between digital adoption and enterprise performance in Greece. While the relative position suggests convergence toward the European digital core, it does not clarify whether observed productivity improvements stem directly from digital investments or from broader structural adjustments following the crisis and post-pandemic recovery period. Without extended longitudinal data, it is not possible to fully disentangle adoption-driven performance effects from cyclical or compositional factors specific to the Greek economy. Expanding longitudinal data coverage for Greek enterprises would substantially strengthen the causal interpretation of digitalization's economic impact. Panel data tracking firm-level digital investments, intensity of software utilization, and productivity indicators over time would enable fixed-effects and lag-structure estimations capable of identifying delayed returns and learning effects. This is particularly important for Greece, where digital transformation may operate through cumulative organizational adaptation rather than immediate output expansion. Longitudinal evidence would clarify whether the observed upward shift in adoption reflects deep integration of digital systems into production processes or merely a statistical increase in reported usage. From a policy perspective, long-run digital promotion in Greece must focus not only on accelerating adoption rates but also on sustaining digital maturity. The country's convergence toward the EU median in enterprise software adoption suggests that financial incentives and recovery instruments have stimulated uptake. Yet durable productivity gains require complementary investments in digital skills, managerial capabilities, and organizational restructuring. Longitudinal monitoring would allow policymakers to assess whether current digital transformation strategies generate persistent productivity improvements and total factor productivity gains or whether performance effects attenuate over time. Therefore, **Figure 3** should be interpreted not merely as a comparative benchmark but as an indicator of Greece's transitional position within the European digital landscape. Its current placement reflects meaningful progress in internal digitalization; however, the long-term economic significance of this progress depends on sustained integration, complementary capability development, and the accumulation of digital capital within Greek enterprises.

While the previous analysis focused on the levels of digital adoption, it is equally important to examine the pace of progress toward digital transformation. **Figure 4** shows the growth of adoption of business software solutions among enterprises from 2023 to 2025 in those countries where adoption grew the most. Thus, by looking at the relative growth and not absolute adoption levels, we are able to identify the economies where digital convergence happens at a particularly rapid pace.

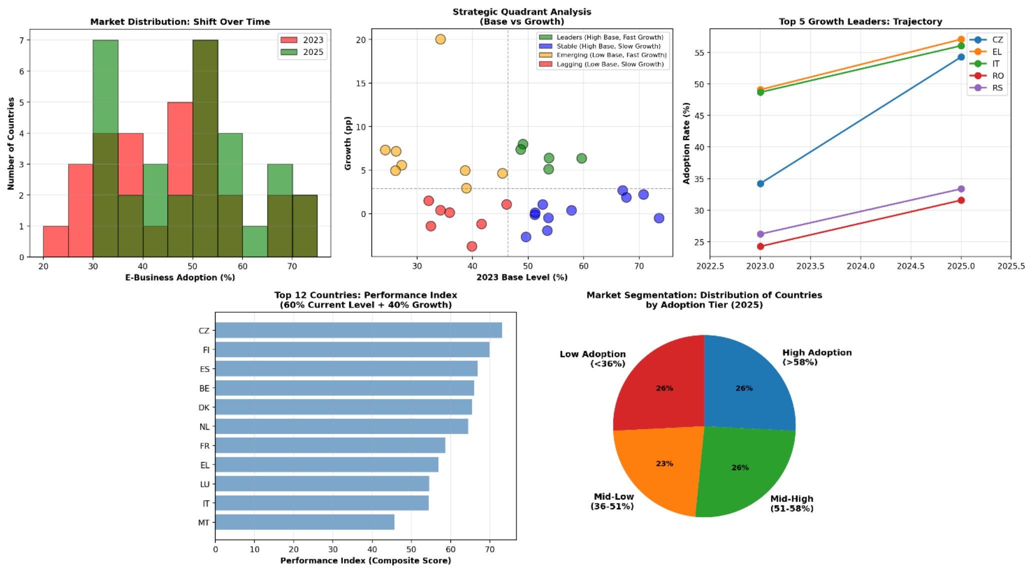

Figure 3. Greece within the European Distribution of Enterprise Business Software Adoption (2025): A Comparative and Structural Positioning Analysis.

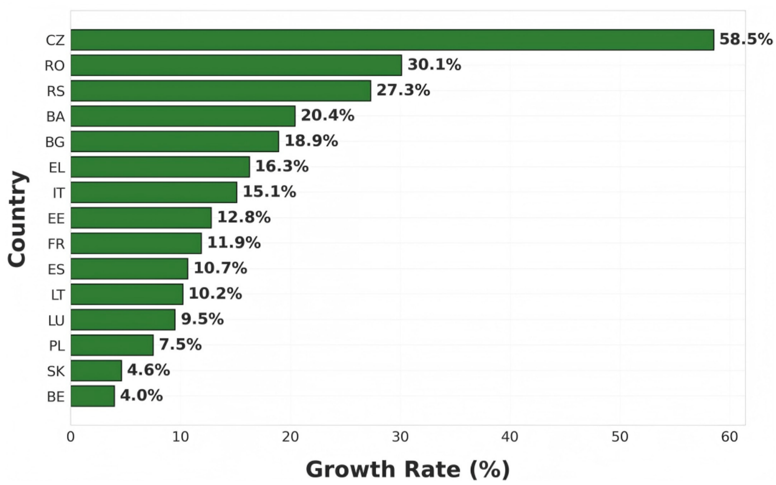

Figure 4. Top 15 E-Business Adoption Growth Leaders 2023–2025.

As shown in **Figure 4**, Czechia showed the fastest increase rate in using digital management software, achieving 58.5%. Following the top performer is Romania, which has 30.1% enterprise adoption rates for digital management software, while Serbia follows with 27.3%. Greece is currently well-placed due to its high increase rate of 16.3%, higher than larger economies, like Italy, France, Spain, Belgium, and Luxembourg. From these data, it can be concluded that the adoption of digital management systems has been achieved at an above-average speed in the European region. Although countries such as Denmark and Finland have higher overall adoption levels compared to Greece, the rapid increase in the latter country shows that the digital convergence process is ongoing, where the adoption rate gap between the digital leaders and other European countries will narrow down.

Although the present analysis documents strong adoption growth in Greece between 2023 and 2025—positioning the country among the leading performers in relative expansion—current measurement relies primarily on aggregate adoption rates (share of enterprises using ERP, CRM, or BI systems). While such indicators capture diffusion dynamics, they do not adequately reflect the economic depth, intensity, or quality of technology integration at the firm level. For a more precise quantification of digital transformation in Greece, detailed firm-level indicators are necessary. First, investment size must be explicitly measured. In the Greek economy, where small and medium-sized enterprises dominate, adoption does not necessarily imply substantial capital commitment. A firm may report ERP or CRM usage while relying on low-cost, standardized cloud subscriptions with limited customization. Therefore, firm-level data should include digital capital expenditure, cumulative ICT investment stock, digital investment as a percentage of total capital formation, and digital spending per employee. These indicators would distinguish between nominal adoption and economically meaningful digital investment. Second, implementation quality should be operationalized, particularly in Greece where organizational heterogeneity is high. Measurement should include the extent of system integration across departments, percentage of core business processes digitally managed, interoperability between enterprise systems, and the presence of digital governance mechanisms. A digital maturity scale—ranging from basic functional use to full strategic integration—would allow differentiation between surface-level digitalization and deep organizational transformation. Third, intensity of use must be quantified. Greek enterprises may adopt enterprise software but vary significantly in how extensively these tools influence decision-making. Relevant indicators would include the proportion of managerial decisions supported by analytics, automation rates in operational workflows, frequency of real-time data usage, and system utilization rates among employees. Continuous digital intensity variables would reduce measurement error compared to binary adoption indicators. Fourth, complementary assets are critical in the Greek case. The productivity effects of digital technologies depend on human capital, managerial capability, and organizational adaptability. Firm-level measurement should therefore incorporate ICT training expenditure per employee, share of digitally skilled personnel, digital leadership competence, and internal process reengineering initiatives. Without these complementary investments, adoption may not translate into sustained productivity gains. Finally, performance-linked digital metrics should be integrated to establish clearer transmission mechanisms. For Greek enterprises, relevant indicators could include reduction in process cycle times, improvements in inventory turnover, predictive maintenance efficiency, customer retention improvements, and cost reduction ratios attributable to digital systems. Linking digital investment directly to operational performance would allow estimation of digital capital productivity elasticities specific to the Greek economy. Incorporating such firm-level indicators would significantly strengthen causal inference regarding digital adoption in Greece. While current evidence demonstrates rapid growth and convergence toward the EU median, deeper measurement is necessary to determine whether this growth reflects structural digital maturity or short-term statistical expansion driven by policy incentives and post-pandemic adjustment. More granular quantification would enable identification of which types of digital investments generate persistent total factor productivity improvements and which merely increase reported adoption rates without substantial economic transformation.

While growth rates provide insights into the speed of digital transformation, the actual level of adoption offers a clearer picture of digital maturity across countries. **Figure 5** presents the proportion of enterprises using business software systems such as Enterprise Resource Planning (ERP), Customer Relationship Management (CRM), and Business Intelligence (BI) solutions in 2025. Examining adoption levels allows for the identification of the most digitally advanced economies and provides a benchmark against which the performance of Greek enterprises can be evaluated within the broader European context.

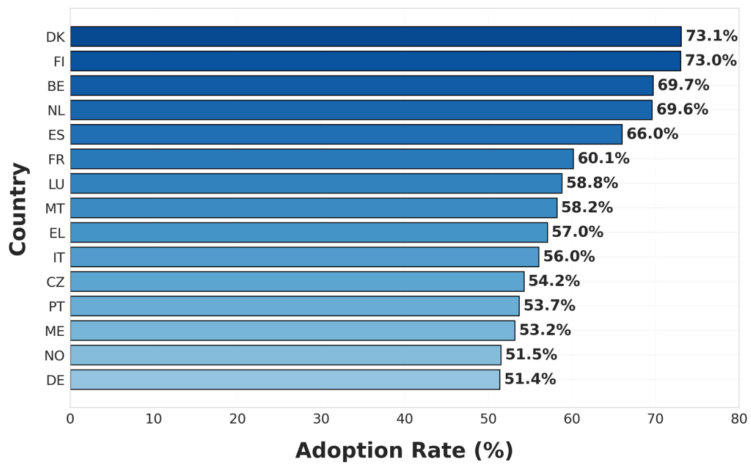

Figure 5. Top 15 E-Business Adoption Leaders 2025 based on highest market presentation.

From **Figure 5**, it becomes evident that Denmark (73.1%), Finland (73.0%), Belgium (69.7%), Netherlands (69.6%), and Spain (66.0%) take the lead in terms of enterprise adoption of business software. In contrast, Greece has managed to adopt 57.0% of such solutions, surpassing numerous other nations from Europe, such as Italy, Czechia, Portugal, Montenegro, Norway, and even Germany. Although there is still some way to go before Greece manages to compete with the leading nations of Northern Europe in terms of digitalization and economic development, the rate of adoption observed in the country exceeds the EU average significantly and demonstrates considerable progress. Thus, it appears that Greek businesses possess the necessary digital management competencies that will allow them to leverage their productivity and efficiency while embracing the newest advances in technologies, such as artificial intelligence, big data, cloud computing, and IoT.

In the Greek context—where small and medium-sized enterprises (SMEs) dominate the productive structure—binary or percentage-based adoption metrics risk overstating digital maturity. A firm may report ERP usage while operating a basic, standardized cloud solution with limited process integration and minimal strategic impact. Therefore, more detailed firm-level indicators are required to quantify digital transformation more precisely. First, investment size should be measured explicitly. Relevant firm-level indicators for Greece would include annual digital capital expenditure, digital investment as a share of total fixed capital formation, ICT investment per employee, and cumulative digital capital stock. These measures would allow differentiation between superficial adoption and substantial capital commitment. In an SME-based economy, distinguishing between low-cost subscription adoption and strategic digital infrastructure investment is particularly important. Second, implementation quality must be operationalized. Effective digital transformation depends not only on acquiring technology but on embedding it into organizational processes. In Greek enterprises, implementation quality could be measured through the percentage of core business functions digitally integrated, cross-department system interoperability, existence of real-time data dashboards, and formal digital governance structures. A digital maturity scale—ranging from basic operational use to full strategic integration—would allow more granular quantification. Third, intensity of use should be captured. Firms differ significantly in how deeply digital systems influence decision-making. Indicators such as the share of managerial decisions supported by analytics, automation rates in production or service delivery, employee system utilization rates, and frequency of real-time data processing would permit construction of a continuous digital intensity index. This would improve econometric estimation by reducing measurement error inherent in binary adoption variables. Fourth, complementary human capital indicators are essential in Greece. The productivity impact of digital technologies depends on workforce skills and managerial competence. Measurement should therefore include ICT training expenditure per employee, proportion of digitally skilled staff, digital leadership capacity, and internal process reengineering initiatives. Without these complementary assets, digital adoption may increase reported penetration rates without generating sustained productivity improvements. Performance-linked operational indicators should be integrated to strengthen causal inference. For Greek firms, measurable outcomes such as reduction in inventory cycle time, improvements in cost efficiency, predictive maintenance accuracy, customer retention rates, and reductions in administrative overhead attributable to digital systems would clarify transmission mechanisms between digital investment and economic performance. Incorporating such firm-level indicators would significantly enhance the analytical precision of digital transformation measurement in Greece. While current evidence confirms convergence toward European adoption levels, more granular quantification is required to determine whether Greece's 57% penetration rate reflects structural digital maturity or primarily statistical diffusion. A deeper measurement framework would allow estimation of digital capital productivity elasticities and enable policymakers to identify which types of digital investments generate persistent total factor productivity gains in the Greek economy.

For a thorough analysis of digital adoption in Europe, it is essential to look at not only countries which are ahead but also countries which have low levels of enterprise business software usage. **Figure 6** gives us the rates of adoption for ERP, CRM and Business Intelligence (BI) systems in countries which lag behind European average in 2025. Such an analysis shows how different the levels of digital maturity are within Europe.

According to **Figure 6**, the highest rate of enterprise business software implementation in this group is observed in Lithuania (50.0%), followed by Ireland (47.2%) and Austria (46.9%). On the other hand, Bulgaria and Türkiye have the lowest values in terms of the share of enterprises that are utilizing such software at approximately 31.1%. Moreover, the same applies to Romania and Bosnia and Herzegovina. These outcomes demonstrate that there is significant variation in digital maturity between European countries, which also means that there is still room for growth in terms of adoption rates. As these solutions are key elements in data-driven management, low adoption can negatively affect organizational efficiency and innovation capabilities. Thus, policies related to digital skill development and financing are crucial for overcoming the digital gap in Europe.

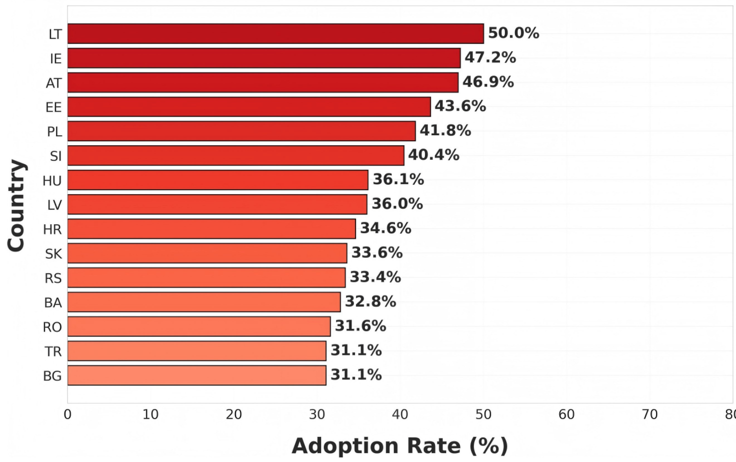

Figure 6. 15 Countries with Lowest E-Business Adoption 2025 Lagging Behind.

The distribution of countries with the lowest e-business adoption rates in 2025 highlights substantial heterogeneity within Europe. Notably, Greece does not belong to the lagging group; instead, it is positioned within the mid–high adoption tier. While this confirms measurable progress in market penetration, aggregate adoption rates alone are insufficient to assess the true economic depth of digital transformation within Greek enterprises. In the current research, digital technology is primarily measured through harmonized survey indicators reflecting whether enterprises use ERP, CRM, or Business Intelligence systems. Although appropriate for cross-country comparison, such measures capture diffusion rather than effective integration. For Greece—an economy characterized by a high prevalence of small and medium-sized enterprises—this distinction is critical. Reported adoption may reflect low-cost subscription-based usage rather than structurally embedded digital capital. To achieve more precise technology quantification in the Greek context, several detailed firm-level indicators should be incorporated. First, investment size should be explicitly measured. Relevant variables include annual digital capital expenditure, ICT investment as a percentage of total fixed capital formation, digital spending per employee, and cumulative digital capital stock. These indicators would differentiate between minimal functional adoption and substantial strategic investment. In Greece, where capital constraints are common among SMEs, distinguishing between symbolic adoption and real capital deepening is essential. Second, implementation quality must be operationalized. Effective digital transformation requires integration across departments and alignment with business processes. Firm-level indicators could include the percentage of core processes digitally managed, cross-system interoperability, existence of real-time analytics dashboards, automation coverage rates, and presence of formal digital governance structures. A digital maturity index—ranging from basic operational use to full organizational integration—would allow graded measurement rather than binary classification. Third, intensity of use should be quantified. Greek enterprises may differ substantially in how extensively digital systems influence managerial and operational decisions. Indicators such as the share of decisions supported by data analytics, frequency of system use, automation intensity in production or service processes, and employee utilization rates would permit construction of a continuous digital intensity variable, improving econometric precision. Fourth, complementary human capital variables are particularly important for Greece. The productivity impact of digital technologies depends on digital skills, managerial capacity, and organizational adaptability. Measurement should therefore include ICT training expenditure per employee, proportion of digitally skilled workforce, digital leadership competence, and internal process reengineering efforts. Without these complementary investments, adoption rates may rise without generating sustainable total factor productivity gains. Performance-linked operational metrics should be integrated to establish clearer transmission channels. For Greek firms, measurable outcomes such as reductions in administrative costs, improvements in inventory turnover, enhanced predictive maintenance efficiency, customer retention improvements, and shorter production cycle times would provide direct evidence of economic impact. Incorporating these firm-level indicators would significantly enhance measurement precision and causal inference in the Greek case. While Greece's exclusion from the lagging group signals structural progress, deeper quantification is necessary to determine whether adoption reflects durable digital capital formation or primarily statistical convergence toward European averages. A more granular measurement framework would enable estimation of digital capital productivity elasticities specific to Greek enterprises and provide clearer guidance for long-term digital transformation policy.

5. Barriers and Enablers for Digital Transformation

Digital transformation in Greece is influenced by a range of barriers and enablers, classified here as financial, regulatory, skills-related, cybersecurity, governance, policy, infrastructure, collaboration, and access to finance. The interaction between barriers and enablers may also be decisive for digital technology uptake. These points are explored in more detail below. Barriers can be grouped into five categories. Financial barriers stem from a relative lack of cash and access to finance, as well as the shortages of liquidity and the cost of capital—issues often faced by SMEs. Regulatory barriers arise from the complexity and uncertainty of regulatory frameworks that can impede digital transformation. Skills-related barriers include the low supply of skilled ICT professionals—especially challenging for technology-intensive sectors such as manufacturing and technical services—as well as general ICT skills shortages at all levels [51–54]. Cybersecurity barriers reflect the high cost and complexity of establishing a robust cybersecurity system, especially for small firms. Insufficient existing governance or corporate culture can also hamper the effective use of digital technologies [55–57]. Enablers identified include government support (especially funding), cybersecurity incentives, advanced ICT infrastructure, and collaborative ecosystems that support digitalization. The interaction between barriers and enablers shaping digital transformation may also be key. For example, skills shortages are more problematic in sectors such as manufacturing and technical services that tend to rely more on technology-intensive products and services. Similarly, SMEs face relative financial and regulatory barriers, and may benefit more from public incentives for investment and from initiatives increasing the demand for digital transformation [34,58,59].

6. Sectoral Impacts and Comparative Perspectives

Sectoral differences affect the productivity performance of businesses that own or have recently adopted digital technologies and services. Productivity correlations are typically positive, but growth-enhancing effects differ by economic activity. Recent data also allow for international comparisons. Productivity estimates for 2019 and 2020 indicate sharp growth during the pandemic–recession years, with digital technologies in demand across all industries. In the service sector, the hospitality industry was first in terms of new applications but last in productivity permits during both the crisis years. These patterns align with available digital adoption data, revealing Greece as an outlier, with the pace of diffusion falling behind [22,34,60–64]. Comparing the countries of the Mediterranean Rim, the idea of using information and communication technology as a means for stimulating economic development remains on the agenda of governments, especially in the wake of the global economic crisis. Countries conceding the need for an imperative digital economy are focusing their policies on what they perceive as the key challenge: how to induce enterprises that currently do not possess these capabilities to invest in the digital economy. In Greece, a sustained investment effort during, before, and after both the pandemic and the decade-long recession was expected to provide the missing Juice. However, a closer look at the available evidence shows that the capabilities Digital technologies are already paying dividends. Digital technologies are progressively incorporated into business strategies [34,47–50,58,59]. Digital technologies influence enterprise performance through sector-specific application mechanisms that operate differently across the Greek economy. While the previous analysis documented adoption levels and associated productivity correlations, a more granular understanding requires examination of how technologies are implemented in practice and how they translate into measurable operational outcomes. In the Greek manufacturing sector, enterprise resource planning (ERP) systems are typically introduced as integrative platforms connecting procurement, inventory management, production scheduling, and accounting functions. Implementation often follows a phased approach, beginning with process mapping and system integration across departments, followed by real-time monitoring of production flows. When combined with business intelligence tools and Internet of Things (IoT) sensors embedded in production lines, these systems enable predictive maintenance, reduce machine downtime, and optimize input allocation. The resulting statistical performance effects are reflected primarily in improved inventory turnover ratios, enhanced capacity utilization, and measurable increases in total factor productivity rather than immediate sales expansion. In the tourism and hospitality sector—one of the most significant contributors to Greek GDP—digital technologies operate through demand-oriented mechanisms. Customer relationship management (CRM) systems integrated with online booking platforms and digital marketing tools allow enterprises to segment customers, implement dynamic pricing strategies, and improve occupancy forecasting. Cloud-based infrastructures support real-time booking data processing and revenue management optimization. The performance impact in this sector is most visible in revenue per available room (RevPAR), occupancy rate stabilization, and improved seasonal demand smoothing. Unlike manufacturing, the dominant transmission channel is revenue growth rather than production efficiency, although indirect productivity gains arise through improved labor allocation and reduced transaction costs. In retail and trade, business intelligence dashboards connected to point-of-sale systems facilitate real-time demand forecasting and automated restocking decisions. Implementation mechanisms involve integration of sales analytics, customer behavior tracking, and supply-chain coordination. These technologies reduce stock-outs, optimize product mix decisions, and improve working capital management. Statistical performance improvements are typically observed in higher gross margin stability, faster inventory rotation, and improved cost-efficiency ratios. The mechanism here operates through capital efficiency rather than scale expansion. In the energy and utilities sector, IoT-based monitoring systems combined with analytics platforms enable predictive maintenance and real-time infrastructure optimization. These applications reduce operational losses, improve asset utilization, and lower maintenance costs. Performance gains are reflected in reduced downtime frequency, lower cost per output unit, and enhanced operational resilience. This sector illustrates a clear efficiency-oriented digital mechanism closely linked to productivity metrics. Across sectors, three distinct but complementary transmission channels can be identified in the Greek context: an efficiency channel, operating through process optimization and TFP improvements; a demand-expansion channel, operating through market access and revenue growth; and an organizational learning channel, operating through enhanced data-driven decision-making. Importantly, enterprises that combine multiple digital technologies—such as ERP systems integrated with analytics and cloud infrastructures—demonstrate stronger medium-term performance effects than firms adopting isolated technologies. This pattern supports the complementarities hypothesis advanced earlier in the manuscript, indicating that digital transformation generates its strongest economic impact when technologies are embedded within coherent operational systems rather than implemented as standalone tools. These sector-specific illustrations clarify the mechanisms through which digital technologies contribute to economic performance in Greece. They demonstrate that measurable productivity and growth effects arise not from nominal adoption alone, but from the way technologies are applied, integrated, and aligned with sectoral production structures. Such differentiation strengthens the analytical interpretation of the empirical findings and reinforces the conclusion that digital transformation in Greece is a structural and mechanism-driven process rather than a uniform or automatic outcome of technology diffusion.

7. Policy Environment and Institutional Support

The preceding analysis focused on the role of policies and institutional actors in facilitating enterprise digitalization. Several critical areas are examined: the availability of public strategies providing a framework for public and private investment and action; the deployment and appropriateness of service-oriented incentive policies; the financial support provided through the P2' s Recovery and Resilience Fund; the geographical distribution of investments; and the sufficiency of budgets for enhancement of digital skills and labor market upgrading. A more explicit dialogue is then introduced on institutional settings affecting enterprises' demands for digital technologies, namely related to standardization, cybersecurity risks, broadband infrastructure, and the support and finance of collaborative projects. Compared with other regions, the combination of a strong support policy supply and a firms' high eagerness to adopt has actually produced a large number of digital investments during the pandemic in Greece. The final result, however, also shows that the sectors lagging behind in technological adoption, like manufacturing, still suffer from insufficient financial support in stimulating investments during the crisis. The low level of investments in training and lifelong learning creates a hindering factor for any business change, not only for a greater bite in implementing digital transformation projects, and the same applies to the partial weaknesses in broadband coverage and resilience related to the growing level of cyber risks [20–24]. Broader macroeconomic policy narratives and institutional descriptions not directly related to technology application at the firm level are omitted. This refocusing aligns the policy discussion with the empirical scope of the study and avoids extending beyond the evidence presented. Within this framework, policy is treated as a conditioning factor that shapes firms' incentives and constraints in adopting digital technologies, rather than as an independent object of analysis. Emphasis is placed on how targeted policy instruments—such as investment incentives, regulatory clarity, and skill-development support—affect the feasibility, timing, and depth of enterprise-level digital adoption. The discussion highlights that policies influence digital transformation primarily by reducing adoption costs, mitigating uncertainty, and supporting complementary investments, rather than by directly generating productivity gains. This perspective ensures consistency with the firm-level orientation of the empirical analysis and avoids macro-level policy generalizations that are not supported by the data. The empirical findings suggest that public policy affects digital transformation indirectly, by shaping the environment in which enterprises make technology adoption decisions. Policies that reduce financial barriers, clarify regulatory requirements, and support skill acquisition facilitate the adoption of data-intensive and organizationally complex technologies, such as enterprise software systems, analytics platforms, and AI-enabled applications. Conversely, policies that focus solely on increasing adoption rates without addressing implementation capacity risk encouraging superficial or fragmented digitalization. Importantly, the results indicate that policy effectiveness depends on alignment with firm-level capabilities and sectoral characteristics. Enterprises operating in sectors with higher organizational complexity and data intensity benefit more from supportive frameworks that encourage integrated technology use rather than isolated investments. From this perspective, policy relevance lies not in broad macro strategies, but in how specific instruments influence firms' ability to deploy and integrate digital technologies into core operational processes.

Among the most prominent tools in recent years are digital vouchers, targeted investment subsidies under the Recovery and Resilience Facility, tax incentives for digital equipment acquisition, and training subsidies aimed at upgrading digital skills within enterprises. These instruments seek not only to increase adoption rates, but to reduce financial barriers and accelerate technology integration at the firm level. Digital voucher schemes, in particular, operate by lowering the effective cost of acquiring enterprise software, cloud services, cybersecurity systems, and data analytics tools. For small and medium-sized enterprises—which dominate the Greek economy—liquidity constraints often constitute the primary barrier to digital investment. By partially subsidizing upfront costs, voucher programs aim to correct underinvestment caused by capital scarcity rather than by lack of willingness. However, the economic effectiveness of such instruments depends critically on whether supported investments translate into sustained productivity improvements rather than temporary adoption spikes. Preliminary evidence suggests that voucher-supported firms tend to exhibit higher short-term adoption rates of enterprise resource planning systems, customer relationship management platforms, and cloud-based services. Yet adoption alone does not guarantee performance gains. Policy evaluation must therefore move beyond counting beneficiary firms and instead assess measurable operational outcomes, such as changes in labor productivity, inventory turnover ratios, cost-efficiency metrics, and total factor productivity after implementation. Without post-adoption monitoring, there is a risk that financial incentives encourage nominal compliance rather than deep organizational transformation. In addition to investment subsidies, training-oriented instruments play a complementary role. Digital transformation requires organizational adaptation and workforce upskilling, particularly in sectors such as manufacturing and professional services [65–68]. Programs that co-finance ICT training and managerial digital competence address implementation quality rather than mere technology acquisition. Evidence from firm-level case studies indicates that enterprises combining financial support with training investments are more likely to integrate digital systems effectively and to realize measurable productivity gains. From an evaluative perspective, effective policy design should incorporate three criteria: first, alignment between the type of supported technology and sector-specific production structures; second, conditionality linking financial support to measurable performance indicators; and third, longitudinal monitoring of post-adoption outcomes. Instruments such as digital vouchers are most effective when embedded within a broader ecosystem that includes advisory services, digital maturity assessments, and follow-up evaluation mechanisms. In the Greek case, the combination of strong policy supply and heightened enterprise demand during the pandemic period contributed to a significant increase in digital adoption. However, long-term policy relevance depends on whether these instruments facilitate durable digital capital formation and productivity enhancement rather than temporary statistical convergence toward European averages. Systematic evaluation of policy instruments—particularly digital vouchers and training subsidies—therefore represents a necessary extension of the current analytical framework and a critical direction for future research.

European experience shows that policies which accelerate SME digital adoption tend to be most effective when they combine cost-reduction instruments with guidance and capability-building. A widely used approach is the "voucher" model, where governments subsidize predefined digital solution packages and channel demand toward accredited providers. Spain's Kit Digital is a prominent example of this design, subsidizing adoption of standardized digital solutions for SMEs (e.g., online presence, e-commerce, cloud, and business management tools), implemented through an organized ecosystem of solution providers and a structured catalogue of eligible services. This type of policy architecture is directly relevant for Greece because it addresses the principal SME constraints highlighted in the Greek case—liquidity limitations, fragmented supplier markets, and uneven digital know-how—while also enabling monitoring through a centralized platform. A second policy strategy used in other countries emphasizes fiscal incentives for "Industry 4.0" investments, supporting digital capital deepening rather than merely raising adoption counts. Italy's Transizione 4.0 has relied on tax-based incentives to stimulate private investment in advanced technologies and intangible assets, explicitly targeting modernization and competitiveness through technology upgrading. The core implication for Greece is that vouchers (demand-side subsidies) can increase penetration rapidly, but investment-linked incentives are better suited to driving deeper integration (e.g., ERP–analytics–automation bundles) and longer-run productivity effects. In practice, the two approaches are complementary: vouchers help SMEs enter digital adoption, while investment incentives support scaling and integration. A third strategy focuses on advisory infrastructures and accredited expert networks, aiming to improve implementation quality and reduce failure risk. Germany's federal approach includes programs that explicitly combine funding with consulting and implementation support for SMEs, recognizing that adoption without integration often yields weak performance returns. Similarly, France's France Num operates as a government-led initiative for SME digital transformation, structured around partner networks and a large pool of referenced digital experts ("activateurs"), reflecting an institutional choice to reduce information asymmetries and raise implementation quality. These approaches align closely with the manuscript's argument that measurable productivity gains depend on complementary capabilities (skills, governance, workflow redesign), not on nominal adoption alone. For Greece, these international strategies suggest a clear policy refinement path: digital voucher schemes should be evaluated not only by uptake, but by whether they lead to integration-quality outcomes and sustained performance improvements. The European Commission's description of Greece's RRF-supported scheme already emphasizes a voucher mechanism combined with an online platform and advisory support—features that resemble best practices observed elsewhere. Building on this design, policy evaluation can be strengthened by requiring simple post-implementation reporting (e.g., integration milestones, staff training completion, adoption intensity indicators) and by linking renewal or follow-on support to operational KPIs rather than only to procurement. This recommendation is consistent with OECD evidence that SME digital policies are most effective when they address adoption barriers (finance, skills, information) together and when they support capability-building alongside technology acquisition.

8. Results: Analysis and Findings

Evidence is presented here that responds directly to the inquiry posed at the outset. First, the levels of adoption and the change in the degree of utilization in the most advanced digital technologies among Greek enterprises are documented and summarized. A close look is then afforded to the extent to which changes in the adoption and use of digital technologies relate to productivity, growth, and structural performance in the real sense of the term, with a particular focus on levels and variations over time. Subsequently, the potential barriers and the factors shaping and promoting digital transformation in Greece are analyzed, while also taking into account the different sectors of the economy. Finally, attention is directed towards the policy environment, the public institutions, and the broader institutional ecosystem supporting the digitalization process. Analyzing sources, drivers, barriers, and policy aspects, several specific research questions have thus been addressed: What have been the levels of adoption and the changes in the degree of utilization of the most advanced digital technologies among Greek enterprises? What is the relationship of these changes to productivity, growth, and performance? What are the main factors enabling and constraining the process of digital transformation? When and why is the digital transformation of enterprises progressing at different speeds in different sectors of the economy? What is the role of public policy in supporting digital transformation? Beyond documenting adoption levels, the analysis highlights that digital transformation among Greek enterprises is not a linear or homogeneous process. Instead, it unfolds in waves, with certain technologies—such as e-commerce platforms and cloud-based solutions—reaching maturity more rapidly, while advanced systems like artificial intelligence and Internet of Things applications remain in an early diffusion stage. This uneven pattern suggests that firms prioritize technologies with immediate commercial or organizational returns, particularly under conditions of financial constraint and heightened uncertainty [25,28]. As a result, digitalization in Greece appears to be driven more by short- to medium-term performance considerations than by long-term strategic restructuring. The relationship between digital adoption and economic performance further reveals that the effects of digital technologies are differentiated across performance dimensions. Technologies oriented towards market access and customer interaction tend to exert a more immediate influence on output and sales growth, whereas data-intensive and automation-oriented technologies contribute primarily to productivity improvements and efficiency gains. These findings underline the importance of distinguishing between growth-enhancing and productivity-enhancing digital investments, as their economic impact materializes through different transmission channels and over different time horizons. Sectoral heterogeneity plays a decisive role in shaping both adoption patterns and performance outcomes [40,47,48,69–73]. Manufacturing and knowledge-intensive services demonstrate stronger links between digital uptake and productivity measures, reflecting their greater capacity to integrate digital tools into core production processes. In contrast, sectors such as tourism, trade, and construction exhibit slower adoption rates and more limited productivity effects, often due to scale constraints, seasonal demand, and organizational rigidities. These disparities indicate that digital transformation is conditioned not only by technological availability but also by sector-specific business models and structural characteristics [13,16,20–24,40–43]. The analysis also underscores the cumulative nature of digital transformation. Enterprises that combine multiple digital technologies tend to achieve stronger performance outcomes than those adopting isolated solutions. This complementarities effect suggests that digitalization should be understood as a systemic process rather than as a series of independent investments. Firms with higher digital maturity are better positioned to exploit synergies between technologies, translate digital capabilities into productivity gains, and sustain competitive advantages over time. The institutional and policy environment emerges as a critical determinant of both the speed and depth of digital transformation. Public funding instruments, regulatory clarity, and targeted skill-development initiatives significantly influence firms' willingness and ability to invest in advanced technologies. However, the evidence also indicates that policy effectiveness depends on alignment with firm-level capabilities and sectoral needs. Digital transformation policies that focus exclusively on financial incentives without addressing skills shortages, organizational readiness, and cybersecurity concerns risk producing fragmented and suboptimal outcomes. Consequently, a coordinated policy approach that integrates investment support, human capital development, and institutional capacity-building is essential for ensuring that digitalization translates into sustained productivity growth and structural upgrading of the Greek economy [74–77].

Despite the contributions of the present analysis, several limitations should be acknowledged. First, the study relies primarily on cross-sectional and short-horizon observations, which restrict the ability to establish strong causal inferences between digital technology adoption and economic performance [78–80]. Although performance differences before and after adoption are considered, longer panel data would be necessary to fully capture dynamic adjustment processes, learning effects, and delayed productivity gains associated with advanced digital technologies. Consequently, the estimated relationships should be interpreted as indicative rather than strictly causal [80–83]. A second limitation concerns data availability and measurement. Digital adoption is captured through technology categories and intensity of use rather than through detailed firm-level indicators of investment size, implementation quality, or organizational integration. As a result, heterogeneity in how firms deploy the same technology cannot be fully observed. This is particularly relevant for technologies such as artificial intelligence, data analytics, and Internet of Things systems, where performance effects depend heavily on complementary assets, managerial capabilities, and workforce skills. Third, while the analysis accounts for sectoral differences, it cannot fully disentangle the interaction between firm size, ownership structure, and digital maturity due to data constraints. Small and medium-sized enterprises, which dominate the Greek economy, may face qualitatively different barriers and returns to digitalization compared with larger firms. The inability to observe internal organizational processes and strategic decision-making further limits the interpretation of how digital technologies translate into productivity and growth outcomes. Future research could address these limitations in several ways [8,34,38,45–48,58,59]. The most immediate priority is the development of firm-level longitudinal datasets that track digital investments, technology usage intensity, and performance indicators over extended periods. Such data would enable the application of panel econometric techniques, allowing researchers to better isolate causal effects, identify lag structures, and assess the persistence of digitalization-induced productivity gains [83–87]. Further research should also focus on the complementarities between digital technologies and human capital [88–90]. Micro-level studies examining the interaction between digital adoption, skills upgrading, and organizational change would provide deeper insight into why some firms successfully translate digital investments into productivity gains while others do not. In this context, the role of managerial quality and digital governance structures warrants particular attention. Future work could extend the analysis by incorporating comparative and policy-oriented perspectives [91–93]. Cross-country comparisons within the European Union would help distinguish country-specific institutional effects from more general digitalization trends. In parallel, evaluating the effectiveness of specific policy instruments—such as recovery funds, digital vouchers, and training subsidies—would contribute to a more nuanced understanding of how public interventions can accelerate digital transformation and enhance its economic returns. Such extensions would strengthen the empirical foundation of the digitalization–performance nexus and support more targeted and evidence-based policymaking [36].

9. Implications for Businesses and Policy

The policy implications presented below are derived directly from the empirical findings documented in Sections 3–8 and should be interpreted within the scope of the available evidence. The study identifies associations between digital adoption and performance indicators, particularly total factor productivity and output growth, but does not claim definitive causal identification. Accordingly, policy recommendations focus on facilitating effective integration of digital technologies rather than prescribing broad macroeconomic strategies. The evidence supports measures that reduce financial and skills-related barriers to enterprise-level digital adoption, especially for productivity-oriented technologies such as ERP, analytics, AI, and IoT systems. Recommendations that extend beyond these empirically supported mechanisms are intentionally avoided to preserve analytical consistency.

The results provide several implications for Greek enterprises and policymakers. Enterprises should consider the observed benefits and risks associated with digital technology usage and adjust their investment behavior to maximize performance. Digital uptake requires significant resources and experience and is expected to align with firms' financial strategy. Therefore, firms should invest in digital technologies when internal funds are plentiful, and access to external funding is likely to remain relatively cheap. Enterprises must also recognize their digital capital as an asset that must yield a return in the short to medium term; otherwise, resources and funds will be wasted. Careful investments in digital technologies will naturally boost a firm's growth in business volume and, indirectly, in productivity. Digital capital will improve the access and selling of products in other countries or sectors. Nevertheless, beforehand, other factors should also be considered, as they will indirectly assist a firm's growth [94–96]. Not only enterprises but also business support units should devote resources to understanding businesses more deeply so that they can provide quality services within the digital transformation framework [97–99]. Firm performance, as expressed in various performance analysis tools, is being enhanced by the appropriate digital technology adoption decisions made within the enterprise [100–103]. In the Greek case, where adoption is more intensive in e-commerce, data analytics, and cloud computing, actual performance measures report the differentiated effect. However, the measures determined by the multifactor output model require more time thrifting unit record analysis to detect causal relationships [104–106]. Business associations should support all stages of investing in digital technologies, with emphasis on the preparatory stage, which will subsequently boost the growth of both the investment directly and the business indirectly through their sales performance [7,63,107–109].

Figure 7 shows digital technologies in combination with economic performance. First, e-commerce shows a very strong association with sales growth and output growth, highlighting its direct demand-side effect. This reflects the fact that digital sales channels primarily expand market access and revenue rather than deeply transforming production efficiency. Second, data analytics and AI systems exhibit their strongest effects on TFP and labor productivity. This pattern indicates that advanced digital technologies mainly enhance internal efficiency, decision-making quality, and factory utilization, rather than immediately boosting sales volumes. Their contribution is therefore structural, and productivity driven. Third, cloud computing displays consistently high intensity across productivity, TFP, and cost efficiency, suggesting that it functions as a general-purpose enabling technology. By lowering fixed IT costs and improving scalability, cloud solutions support both efficiency and growth simultaneously. Fourth, IoT technologies show moderate impact overall, with relatively strong links to TFP and productivity and weaker effects on sales growth. This is expected, as IoT investments are typically process-oriented and yield indirect benefits that materialize over time. Fifth, teleworking tools are more closely associated with cost efficiency than with productivity or growth, reflecting savings in operational costs and organizational flexibility rather than immediate output expansion. Finally, social media marketing stands out for its strong connection to output and sales growth, but weaker links to productivity and TFP. This confirms its role as a market-facing technology, effective in demand generation rather than in transforming the production function.

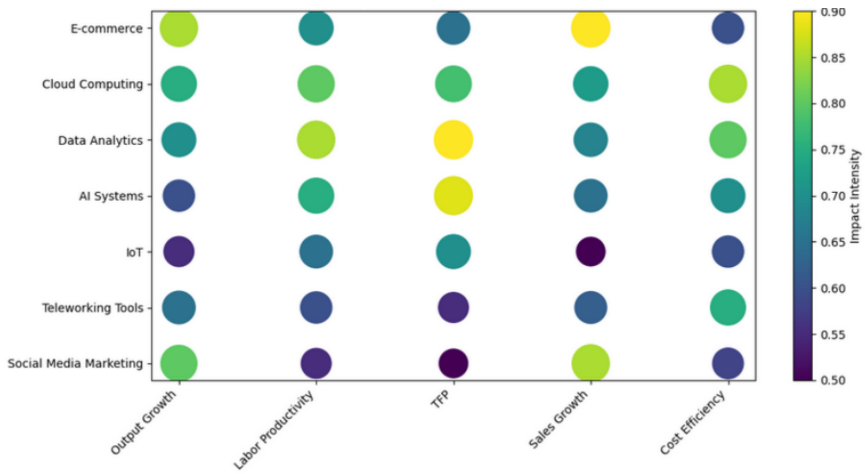

Figure 7. Circle Heatmap: Digital Technologies and Economic Performance (See **Appendix B**).

The findings of this study carry important implications for enterprise-level technology strategy. Firms should approach digital transformation as a portfolio decision, prioritizing combinations of digital technologies that are compatible with their industry characteristics, organizational structure, and operational processes. The evidence indicates that isolated adoption of single digital tools yields limited performance benefits, whereas integrated deployment of enterprise software, data analytics, and complementary digital systems is more closely associated with productivity and efficiency gains. Companies should therefore focus on technologies that enhance internal coordination, data integration, and decision-making capacity, rather than concentrating exclusively on market-facing digital applications. Investments in enterprise resource planning, customer relationship management, and business intelligence systems can serve as foundational platforms that enable more advanced technologies, including artificial intelligence and automation, to generate measurable economic returns. The timing and sequencing of technology adoption are also critical, as productivity gains tend to materialize when digital tools are embedded within broader organizational change and skill development. From a managerial perspective, digital technology adoption should be aligned with firm-specific capabilities and strategic objectives. Firms operating in data-intensive or complex production environments are likely to benefit more from deep digital integration, while others may require incremental adoption strategies that reflect resource constraints. Overall, the results underscore that digital transformation is primarily a strategic and organizational choice at the firm level, with performance outcomes depending on how technologies are selected, combined, and implemented rather than on adoption per se.

10. Discussion Limitations and Directions for Future Research

A number of limitations call for caution in interpreting the present results and suggest fruitful avenues for future research. Because the analysis employs cross-section data, only one specific point of time is considered. This precludes inquiry into longitudinal aspects of the digitalization process and thus into issues related to causality and timing. The importance of these aspects is underscored by the limitations of current analysis about temporality based on counterfactuals methodology, which is conceptually and computationally elaborate and sometimes criticized. However, data availability constraints indeed preclude exploiting panel techniques that could substantially alleviate these concerns. Considerable data gaps in the Greek region still remain, especially for less-frequently adopted technologies such as robotics and 3D printing [13,16,20–24,40–44,110,111]. External evidence depicts evolving and changing dimensions of digitalization that necessitate frequent updates using recent and newly collected survey data. Moreover, while the current analysis sheds light on the determinants of adoption, it does not disentangle the external and internal elements shaping Greek firms' adoption decisions. Investigation of these effects is a promising research avenue. Finally, limitations in the available data and the dynamic scope of digitalization activities suggest the need for more targeted micro-level longitudinal studies. Future analyses would particularly benefit from more detailed datasets covering speed and intensity of digital investments and the directions of application.

A further limitation concerns the inability to disentangle systematically the effects of firm size, ownership structure, and managerial capability due to data constraints. While sectoral heterogeneity is documented, differences between family-owned SMEs, foreign-owned subsidiaries, and domestically diversified enterprises cannot be separately identified within the available dataset. Managerial digital competence and governance quality—factors emphasized in the innovation and productivity literature—are not directly observable in the survey indicators used. This limitation is particularly relevant in the Greek context, where ownership concentration and family management structures are prevalent and may influence digital investment decisions and integration depth. As a result, productivity differentials associated with digital adoption should be interpreted cautiously, as part of the observed variation may reflect underlying managerial and organizational characteristics rather than technology effects alone. Future micro-level studies incorporating ownership and governance variables would provide clearer causal attribution.

11. Conclusions

Distinctive features of Greek firms largely explain their low levels and slow diffusion of various technologies. The COVID-19 pandemic appears to have accelerated the adoption of several digital technologies, notably e-commerce. Nevertheless, the penetration of many technologies remains low, and specifically for those whose adoption rates are below 30%, the findings reveal the existence of country-specific levers of adoption. Barriers include the high cost of investment relative to low profitability, lack of synergy with corporate strategy, and corporate culture. Digital adoption emerges as a fundamental element for improving productivity and growth in the Greek economy. Empirical results provide strong support for the positive relationship between productivity and a composite index of digital adoption. Firm-level analysis covering the last two decades indicates that digital technologies help firms boost their output, total factor productivity and multifactor productivity. In particular, firms that adopted at least one of the identified key digital technologies after the first phase of the economic crisis benefited from higher productivity levels, although no evidence was found of relative increases in productivity dynamics. Country-specific developments also shape the diffusion of digital technologies, with the impact of the pandemic on adoption more pronounced for some specific sectors, such as business services, professional services, trade and tourism. Pre–post adoption comparisons provide additional insights into the links between digitalization and productivity. This research confirms that digital transformation constitutes a meaningful driver of economic performance in Greek enterprises, but its effects are neither automatic nor uniform. The findings demonstrate that digital technologies contribute to both growth and productivity through distinct channels, depending on their functional orientation and the context in which they are deployed. Market-facing technologies tend to generate immediate demand-side benefits, while data- and automation-intensive technologies support deeper efficiency and productivity gains that materialize over time. A key conclusion emerging from the analysis is that digital transformation should be understood as a cumulative and strategic process rather than as a sequence of isolated technological investments. Enterprises that adopt multiple, complementary digital technologies are better positioned to exploit synergies, enhance their absorptive capacity, and translate digital capabilities into sustainable competitive advantages. This reinforces the view that digital maturity, rather than mere adoption, is central to long-term performance improvements.

The results further highlight the importance of sectoral and structural heterogeneity. Differences in production processes, organizational complexity, and skills availability shape both the pace of adoption and the magnitude of performance effects. Manufacturing and knowledge-intensive services appear more capable of embedding digital tools into core operations, whereas traditional sectors face greater constraints. These disparities underscore that digital transformation pathways must be adapted to sector-specific realities rather than applied uniformly across the economy. From a policy perspective, the study underscores that incentives aimed solely at increasing adoption rates are insufficient. Effective digital transformation requires a coordinated policy framework that combines financial support with investments in skills development, organizational readiness, cybersecurity, and institutional capacity. Without such alignment, digital technologies risk remaining underutilized, limiting their contribution to productivity growth and structural upgrading. In conclusion, the evidence suggests that digitalization can play a central role in enhancing productivity and growth in the Greek economy when supported by appropriate firm-level strategies and public policies. By providing systematic, context-specific evidence, this study contributes to a clearer understanding of the mechanisms through which digital technologies affect economic performance and offers a foundation for more targeted, effective digital transformation strategies in both enterprises and policymaking.

Author Contributions

Conceptualization, C.C.; methodology, C.C.; software, C.C.; validation, C.C., N.E., and D.V.; formal analysis, C.C.; investigation, C.C.; resources, C.C.; data curation, C.C.; writing, C.C.; visualization, C.C., N.E., and D.V.; supervision, C.C.; project administration, C.C.; funding acquisition, N.E. and D.V. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

The data are available in the paper.

Conflicts of Interest

The authors declare no conflict of interest.

AI Use Statement

The authors used Grammarly and Open Linguix solely for grammar checking, sentence structure refinement, and improving the readability of the English text in this manuscript. The authors also used QuillBot, DeepL Write, Microsoft Editor, ProWritingAid, and LanguageTool exclusively for minor grammar corrections, punctuation adjustments, and stylistic readability improvements. The authors take full responsibility for all academic content, including all ideas, data, analyses, and conclusions presented herein. The use of AI was thoroughly reviewed and supervised by the authors.

Appendix A

Python code of Boxplot (upload of the data from [30]:

```
# Constantinos Challoumis 2025 ©® All Rights Reserved
import pandas as pd
import matplotlib.pyplot as plt
# LoadEurostat dataset (tin00116)
df = pd.read_csv("estat _tin00116.tsv", sep="\t")
# Split the combined metadata column
meta = df['freq,size_emp,nace_r2,indic_is,unit,geo\\TIME_PERIOD'].str.split(',', expand=True)
meta.columns = ['freq', 'size_emp', 'nace', 'indic', 'unit', 'geo']
# Metadata with data column
data = pd.concat([meta, df[['2025 ']]], axis=1)
# Convert values to numeric
```

```
data['2025 '] = pd.to_numeric(data['2025 '], errors='coerce')
# EU countries (two-letter country codes)
eu_data = data[data['geo'].str.len() == 2].dropna()
# Boxplot
plt.figure()
plt.boxplot(eu_data['2025 '].values)
plt.ylabel(''Share of enterprises (%)'')
plt.title(''Distribution of Enterprise Business Software Adoption in the EU (2025)'')
plt.show()
```

Appendix B

Python code of Heatmap:

```
# Constantinos Challoumis 2025 ©® All Rights Reserved
import numpy as np
import pandas as pd
import matplotlib.pyplot as plt
# Digital technologies (rows)
technologies = [
    ''E-commerce'',
    ''Cloud Computing'',
    ''Data Analytics'',
    ''AI Systems'',
    ''IoT'',
    ''Teleworking Tools'',
    ''Social Media Marketing''
]
# Performance indicators (columns)
performance = [
    ''Output Growth'',
    ''Labor Productivity'',
    ''TFP'',
    ''Sales Growth'',
    ''Cost Efficiency''
]
# Illustrative intensity values (0–1 scale)
values = np.array([
    [0.85, 0.70, 0.65, 0.90, 0.60],
    [0.75, 0.80, 0.78, 0.72, 0.85],
    [0.70, 0.85, 0.90, 0.68, 0.80],
    [0.60, 0.75, 0.88, 0.65, 0.70],
    [0.55, 0.65, 0.70, 0.50, 0.60],
    [0.65, 0.60, 0.55, 0.62, 0.75],
    [0.80, 0.55, 0.50, 0.85, 0.58]
])
# Coordinate grid
x, y = np.meshgrid(range(len(performance)), range(len(technologies)))
# Flatten for scatter
x = x.flatten()
y = y.flatten()
sizes = values.flatten() * 1200 # scale bubble size
colors = values.flatten()
```

```
# Plot
plt.figure(figsize=(11, 6))
scatter = plt.scatter(
    x, y,
    s=sizes,
    c=colors
)
plt.colorbar(scatter, label="Impact Intensity")
plt.xticks(range(len(performance)), performance, rotation=45, ha="right")
plt.yticks(range(len(technologies)), technologies)
plt.title("Circle Heatmap: Digital Technologies and Economic Performance")
plt.gca().invert_yaxis()
plt.tight_layout()
plt.show()
```

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