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The Role of Digital Infrastructure and Skills in Enhancing Labor Productivity: Insights from Industry 4.0 in the European Union

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Abstract: The adoption of Industry 4.0 technologies supports the digital transformation of production processes, making them more efficient. This study examines how digital infrastructure, digital skills, and the use of cloud technologies influence labor productivity in European Union countries. Using econometric methods, including linear regressions and fixed-effects panel regressions, the analysis highlights the important role digital skills play in boosting productivity. It also identifies the adoption of cloud solutions as a catalyst for process efficiency, while widespread high-speed internet coverage supports the connectivity of smart systems. However, variations in the development of digital infrastructure and workforce readiness across EU member states present challenges to overall labor productivity. The study concludes that strategic investments in automation and digital infrastructure, along with improving the workforce's digital skills, are essential to making Industry 4.0 a key pillar of economic competitiveness. By examining how workforce digital skills and certain Industry 4.0 technologies affect labor productivity, this research adds valuable insights to the specialized literature.

Keywords: Industry 4.0; labor productivity; digital infrastructure; digital skills; cloud technology adoption; internet coverage; digital transformation; advanced technologies

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1. Introduction

Industry 4.0 represents a major digital transformation in society. It relies on advanced technologies, such as the Internet of Things (IoT), big data, artificial intelligence (AI), and machine learning. These innovations help organizations improve their operations and increase productivity. However, implementing these technologies also requires new skills from the workforce and, sometimes, significant financial investments.

In the context of the digital transition promoted by Industry 4.0, the technologies in use exert a complex influence on employment. Automation leads to a reduction in jobs within certain economic sectors. This dual situation calls for a careful analysis of how these technologies reshape the economic structure. Therefore, it is essential to identify and understand how Industry 4.0 technologies contribute to change across various economic sectors, integrating aspects of automation, innovation, and the development of professional skills.

The shift toward more efficient industrial processes and the rise of smart factories depend on strong digital infrastructure, including widespread high-speed internet access and the adoption of cloud solutions. These tools help to lower costs and increase competitiveness in modern industries. However, differences in digital infrastructure and the skill levels of the workforce across the European Union influence how fully Industry 4.0 technologies are adopted. With this in mind, we pose the following research question:

RQ: How do digital factors, such as internet coverage, digital skills, and the adoption of cloud technologies, affect labor productivity in the context of Industry 4.0?

This study explores how adopting Industry 4.0 technologies affects labor productivity. By using econometric methods, it highlights the influence of specific technological factors on productivity and also examines the challenges tied to workforce adaptation. A comparative analysis of EU member states helps pinpoint best practices and offers recommendations for both policy and organizational strategies, aiming for the smoother and more sustainable integration of advanced technologies into the European economy.

This study brings an original perspective through a differential analysis of technological factors that influence labor productivity in European Union member states, while also highlighting regional disparities. Rather than focusing solely on technology infrastructure, it emphasizes digital literacy as a key driver of productivity. In doing so, it shows how investments in both digital skills and infrastructure can lead to differences in productivity from one country to another.

The article is structured as follows: the introduction sets the theoretical context of the transition to Industry 4.0, followed by a review of the relevant literature. Next, it presents the econometric methodology and the data used. The Section 4 then looks at the role of digital infrastructure, skills, and cloud adoption in improving labor productivity. Finally, the Section 5 summarizes the practical implications and proposes recommendations for public policies and organizational strategies.

2. Literature Review

Industry 4.0 represents a significant shift in how processes are conducted within industrial sectors. The integration of advanced technologies, such as the IoT, big data, AI, and machine learning helps reduce costs and optimize production processes. However, adopting these technologies also brings challenges, particularly in adapting workforce skills and, in some cases, incurring substantial implementation costs [1].

A key factor in Industry 4.0 implementation is digital infrastructure, which stands as one of the main pillars for adopting new technologies. High-speed internet and the IoT are pivotal factors in the digitization process [2], as they enable fast device connectivity and real-time data collection, which can then be transformed into actionable insights that optimize production processes. In addition, integrating IoT with big data plays an important role in driving digital transformation for businesses, allowing them to identify new opportunities for innovation and develop effective digitalization strategies [3]. However, differences in digital infrastructure between countries affect the pace of digitalization and limit the capacity to adopt new technologies [4]. If these gaps persist and widen, they could intensify technological and economic disparities, especially in the absence of policies that promote digital infrastructure development.

The authors of [5] point out that successfully adopting new Industry 4.0 technologies requires strong digital skills. In other words, it increases the demand for highly qualified workers, while reducing the demand for lower-skilled positions. The authors of [6] emphasize the importance of training and adapting workforce skills, so they can operate Industry 4.0 technologies effectively.

According to a Eurostat report [7], integrating new technologies boosts industrial productivity. The rapid adoption of cloud technologies leads to operational flexibility and lower associated costs [8].

The authors of [9] warn that jobs involving repetitive tasks or medium skill levels are most at risk when organizations automate using Industry 4.0 technologies. In a similar vein, a McKinsey report [10] shows that around 60% of current jobs have tasks that could be automated. For this reason, it is essential to find a balanced approach.

This study aims to understand how adopting Industry 4.0 technologies influences labor productivity, competitiveness, and labor market dynamics in the EU. Taking an integrated look at the key factors is crucial to turning Industry 4.0 into a driver of sustainable development [1,4].

Adopting an integrated approach that combines digital infrastructure, technological expertise, and cloud solutions transforms Industry 4.0 into a true driver of sustainable development [1,4]. Implementing Industry 4.0 technologies leads to more efficient production systems by cutting back on material and energy waste, thus supporting the transition toward a circular economy [11].

According to [12], integrating IoT, AI, blockchain, and cloud computing strengthens operational sustainability, having a positive impact on resource management and reducing environmental footprints. The authors of [13] underline that Industry 4.0 plays a key role in advancing sustainable economic development by accelerating the process of minimizing ecological impact.

Moreover, digitizing financial and non-financial reporting processes, supported by cloud technologies and big data analytics, significantly enhances the quality of information provided to decision makers and increases the transparency of organizations' sustainability performance [14].

The adoption of Industry 4.0 technologies has a more substantial impact in transition economies, with greater development potential compared to developed economies [15]. Due to differences in the level of digitalization among EU countries, there is a need for policies that reduce these gaps to fully leverage the benefits offered by Industry 4.0 [16]. In this context, the accelerated transformations driven by Industry 4.0 adoption require the adequate development of workforce skills [17] to keep up with the pace of technological advancement. At the EU level, initiatives have been adopted [18,19] that allocate significant resources to reduce workforce skill gaps in line with Industry 4.0 requirements. The necessity for professional training strategies to adapt to new industrial demands is also emphasized by [20,21].

Although digital transformation can eliminate certain jobs by boosting productivity, it also creates new opportunities for workers with advanced digital skills. This situation highlights the need for targeted training and upskilling strategies to ensure a smooth transition toward a workforce suited for the digital economy [22].

According to human capital theory [23], investing in education and developing digital competencies can raise employee productivity and foster innovation. From a sociological standpoint, the digital divide theory [24] stresses that digital infrastructure and technology access alone are insufficient if users do not possess the skills necessary to fully leverage these tools. Moreover, case studies in highly digitalized economies, such as Germany, the Netherlands [25], South Korea, and China [22,26], show that digitalization significantly affects labor productivity, provided it is supported by education and training policies aligned with emerging technological needs [27,28].

Through the implementation of the "Industrie 4.0" initiative in Germany, digitalization led to a 15–20% increase in productivity across advanced industrial sectors [4]. In other countries with similar digital infrastructure, these benefits were less pronounced, primarily due to the absence of robust training policies [27].

Previous studies, such as [1,4], have concentrated on the technological advantages and cost reductions associated with Industry 4.0. However, they do not explore in depth the challenges related to workforce skill adaptation and the disparities among different countries. Similarly, while [5,6] highlight the importance of professional training, they do not thoroughly address the policy measures needed to bridge these gaps.

The unique contribution of our study lies in its integrated approach to examining how Industry 4.0 technologies affect labor productivity, competitiveness, and labor market dynamics within the European Union. By combining an analysis of digital infrastructure with an assessment of the need for digital skill development and wage levels, an essential factor in adopting advanced technologies, our study offers a more holistic perspective [16–19,29,30].

2.1. Internet Coverage: The Foundation of Digitalization and Productivity Growth

A key component of digital infrastructure is the breadth of internet network coverage, which enables the interconnection of various Industry 4.0 technologies. According to studies by the OECD [31] and references from [32,33], broad network coverage significantly boosts production productivity. It also helps lower operational costs.

However, due to existing disparities among EU member states, the integration of Industry 4.0 technologies is uneven. According to one study [34], one viable solution to reduce or eliminate these gaps is to intensify the development of digital infrastructure in regions where it is lacking.

Developing digital infrastructure not only boosts production productivity but also fosters a more adaptable work environment, providing a solid foundation for digitalization and the transition to Industry 4.0 [35]. Additionally, investments in education, healthcare, and international trade play a vital role in increasing labor productivity [36].

Hsieh and Goel [37] examined the impact of internet usage on labor productivity growth in 28 OECD countries, including the United States, between 2001 and 2016. Their findings suggest a moderate effect that varies depending on the economic context. Factors such as internet access, computer use in organizations, and investments in digital infrastructure contribute to modernizing production and enhancing labor productivity [38].

Regions that have consistently invested in digital infrastructure, such as certain industrialized areas in Asia and Europe, are seeing positive shifts in their production processes as a result of digitalization [35,39]. The authors of [40] emphasize the importance of developing digital infrastructure and enhancing digital skills in a competitive environment to ensure high levels of productivity. Similarly, the authors of [41] underscore the importance of policies that promote the adoption of new technologies to reduce productivity gaps between small and large enterprises. Given the crucial role that internet infrastructure plays in the digitalization process and the adoption of Industry 4.0 technologies, the following hypothesis has been formulated:

H1. *High-speed internet coverage positively contributes to the increase in labor productivity.*

Endogenous growth theory [42] underscores the importance of technologies and digital infrastructure in driving innovation and economic productivity. High-speed internet serves as a catalyst for growth, with countries enjoying widespread broadband coverage achieving noteworthy productivity gains, particularly in knowledge-based industries [41].

A study by Czernich et al. (2011) [43] found that a 10% increase in broadband adoption rates corresponds to a 0.9–1.5% rise in per capita GDP among 25 OECD countries from 1996 to 2007. This points to a positive link between expanded broadband use and labor productivity.

Subsequent research reinforces this connection, emphasizing that it is not just the availability of broadband but also how it is utilized that matters. Gallardo et al. (2021) [44] indicate that adoption and digital inclusion metrics have a stronger influence on labor productivity than measures based merely on speed or coverage. A comparative analysis of 14 European countries by the authors of [45] shows that broadband usage intensity within firms positively correlates with productivity, with a more pronounced effect in manufacturing than in services.

Christensen's disruptive technology model [46] explains how extensive high-speed internet access supports the adoption of digital solutions, such as AI, data analytics, and process automation. These technologies reduce decision-making times and improve coordination among teams and distributed production units. Research from Germany and the Netherlands [27] suggests that digitalizing production processes boosted labor productivity in manufacturing by 18%, largely due to better connectivity and integrated supply chains.

However, according to digital divide theory [24], internet access alone does not ensure uniform productivity growth across regions. If digital infrastructure development is not accompanied by digital training programs and investments in workforce skills, productivity can decline. Studies in emerging economies [22] reveal that in areas where digital infrastructure expanded rapidly but digital skills lagged, the effect of high-speed internet on productivity was limited.

2.2. Digital Skills: The Driving Force Behind the Integration of Industry 4.0 Technologies and Productivity

The successful adoption of Industry 4.0 technologies hinges on the digital skills possessed by the workforce involved. According to the authors of [47], adapting to new technological demands requires that employees have the necessary skills to navigate this transition. If professional training programs do not keep pace with technological advancements, significant gaps can emerge between highly skilled workers and those with lower qualifications [5].

Professional training initiatives must be capable of responding to the technological transformations brought about by Industry 4.0 adoption to minimize the risk of labor market polarization [48]. The authors of [49] demonstrate that a high level of digital skills not only facilitates the transition to new technologies but also helps bridge gaps between different regions. Additionally, the authors of [50] highlight that European initiatives focused on employee skill development can reduce barriers to implementing Industry 4.0 technologies.

Furthermore, training programs aimed at young people to develop digital competencies enable organizations to adapt more swiftly to technological changes [51].

Information literacy helps employees adapt to emerging digital technologies, playing a critical role in the transition to Industry 4.0. It goes beyond technical skills and includes cognitive and analytical abilities that allow employees to thrive in highly digitized environments. Recent studies [52–54] show that an organization's level of information literacy influences how quickly it can implement digital and automated solutions. Consequently, information literacy should be built into professional training strategies and educational policies designed to prepare the workforce for new technological demands.

Previous studies have shown that labor productivity is influenced in different ways, depending on the category of digital skills. Important skillsets in the digital economy include programming, data analysis, and information literacy. One study [55] found that employees with advanced data analysis skills significantly boost the operational efficiency of technology-based companies. Consequently, the impact of digital skills on labor productivity should be examined not only at a general level but also according to the specific skills employees possess.

Given the critical role that digital skills play in integrating Industry 4.0 technologies, the following hypothesis has been formulated:

H2. *The level of digital skills within the workforce significantly impacts the increase in labor productivity.*

According to human capital theory [23], investing in education and training positively influences labor productivity growth and stimulates innovation. In a digitalized economy, digital skills are essential for effectively leveraging technologies, analyzing data, and using AI in an ethical manner. Recent research indicates that economies with a digitally skilled workforce achieve substantially greater productivity gains than those lacking such capabilities [22].

The dynamic capabilities model [56] shows that organizations developing their employees' digital skills more rapidly can adapt more easily to technological change. This approach also provides a competitive advantage by boosting productivity. A study in the German manufacturing sector found that companies with well-defined strategies for enhancing employees' digital skills realized a 15–20% increase in labor productivity compared to their counterparts [4].

According to Van Dijk (2005) [24], employees must possess the necessary digital skills to make effective use of new technologies and drive labor productivity growth. One study [22] reports that, in China, industries emphasizing digital skill development maintained their competitiveness; whereas, those that did not experienced drops in productivity and, in some cases, a rise in technological unemployment.

2.3. Cloud Technology Adoption: Supporting Flexible and Scalable Solutions for Enhanced Performance

An important aspect in optimizing production processes is the use of cloud technologies. These allow for highly scalable and flexible solutions that cut operational costs and enable more efficient resource management [8]. Yet, cloud adoption rates vary across EU member states, underscoring the need for policies that encourage the wider integration of these technologies [31]. Cloud-based enterprise resource planning (ERP) systems also play a crucial role in digitally integrating organizational processes. They give real-time access to information, making a significant contribution to gaining a competitive edge [57]. Adopting cloud-based solutions transforms expenses related to purchasing expensive hardware into operational costs, eliminating the need for organizations to buy servers or other physical infrastructure components. This approach makes certain software solutions more accessible and supports the large-scale implementation of advanced technologies in production processes [58].

One study [59] shows that companies adopting cloud solutions enhance both their profitability and market value, with the long-term impact proving even stronger. However, these benefits require significant initial investments, including employee training. Cloud technologies bring numerous advantages, and intelligent manufacturing (IM), combining AI, big data analytics, cloud computing, and the IoT, has become increasingly important for boosting labor productivity. Research [60], which focuses on Chinese firms, indicates that adopting IM exerts a significant positive effect on labor productivity. These findings suggest that cloud technologies and IM play a key role in modernizing production processes and improving organizational performance.

Furthermore, the authors of [61] demonstrate that investment in information and communication technology (ICT) capital and digital infrastructure can mitigate the negative effects of the informal economy. Such investments expand resource access, reduce coordination costs, and help integrate informal sectors into global value chains. However, the slow adoption of digital technologies in some economies continues to limit productivity gains.

Given the role that cloud technologies play in developing scalable and flexible solutions, the following hypothesis has been formulated:

H3. *The adoption of cloud technologies has a positive effect on labor productivity.*

Transaction cost theory [62,63] explains how the use of cloud technologies reduces expenses related to IT infrastructure, data management, and the coordination of production activities. According to [57], companies that have integrated cloud solutions have seen a 12–15% increase in labor productivity compared to those that have not.

The dynamic capabilities model [56] offers insight into how cloud adoption grants organizations greater flexibility in managing business processes. Research on firms in Germany and the Netherlands shows that implementing cloud-based ERP systems led to a 20% drop in operating costs, as well as a rise in labor productivity through automating administrative and production tasks [4].

Innovation diffusion theory [64] highlights that the uptake of cloud technologies differs from one organization to another, depending on factors like organizational culture, digital skills, and existing infrastructure. Studies on small- and medium-sized enterprises [22] suggest that, while cloud technologies can significantly boost productivity, the impact is stronger in firms that invest in employee training and maintain flexible organizational structures.

3. Research Methodology

This study employs quantitative econometric methods to explore the impact of Industry 4.0 on the European economy, focusing on the factors that drive labor productivity within the context of digital transformation. To assess how Industry 4.0 technologies affect labor productivity and employment in the European Union, we conducted regression analyses using data from the Eurostat database [7]. The study covers the period from 2015 to 2023 and includes all 27 EU member states (Appendix A). The analyses were performed using Stata/SE 14.2 software.

The variables used in the models analyzing labor productivity in the Industry 4.0 era are detailed in Table 1. Labor productivity (LP) is measured as the ratio of GDP to the total number of industrial employees, serving as an indicator of human resource productivity. Internet coverage (IC), a crucial component of digital infrastructure, facilitates the connectivity needed for implementing IoT systems and smart factories [1]. Studies show that employees with advanced digital skills make a significant contribution to productivity growth, highlighting the importance of investing in workforce training [5,6]. The adoption of cloud technologies (CA) acts as a catalyst for productivity by reducing operational costs and increasing the flexibility of industrial processes [8].

Included in the models is the logarithmic average salary (LN_SA), which reflects the overall qualification level of the workforce and industrial development. Industries with higher salaries are more likely to adopt advanced technologies, thereby influencing productivity [5,34]. The percentage of enterprises with a very high digitalization index (DI) was used to weight the observations, providing a realistic view of digital integration differences within the European Union [1,4]. Weighting allows the analysis to adjust based on the actual level of digitalization, highlighting areas where additional investments are needed.

One of the main objectives of this study is to examine how digitalization affects labor productivity. The relationship among digital infrastructure, digital skills, and workforce productivity can be shaped by factors not directly observed in the data, potentially leading to endogeneity issues. In other words, while digitalization may influence labor productivity, the reverse can also be true, more productive economies may be more likely to invest in digitalization. To avoid such distortions and obtain more precise estimates, we used a fixed-effects econometric model, which eliminates constant country-level influences and focuses on variations over time. We also applied robust regressions and conducted sensitivity tests to ensure our results remain consistent and are not driven by omitted variables.

This research utilizes several econometric techniques, including simple linear regressions, robust regressions, and fixed-effects panel models, to examine the relationship between Industry 4.0 technology adoption and labor productivity. The use of panel models is justified by their ability to capture the complexity of relationships between variables and to address econometric issues, such as heteroscedasticity and serial correlation [65]. Robust regressions are employed to handle high data variability and provide accurate estimates, even when there are deviations from the constant variance assumption [66]. Fixed-effects panel models eliminate constant and unobserved influences specific to each country, allowing for the more precise estimation of the relationships between variables [67]. In the context of Industry 4.0, where the level of digital technology integration varies significantly among economies, the use of econometric techniques is essential for obtaining robust results [68].

Model 1 is a weighted linear regression model without a control variable, where the dependent variable is labor productivity (LP), and the independent variables are cloud adoption (CA), internet coverage (IC), and digital skills (DS). The weighting variable is the digital index (DI).

$$\begin{aligned} &\text{LaborProductivity}\sqrt{\text{Digital Index}} \\ &= (\beta_0 + \beta_1\text{InternetCoverage} + \beta_2\text{DigitalSkills} + \beta_3\text{CloudAdoption})\sqrt{\text{Digital Index}} \\ &+\epsilon\sqrt{\text{Digital Index}} \end{aligned} \quad (1)$$

Model 2 is a robust linear regression model with the control variable logarithm of salary, weighted by the digital index (DI). The dependent variable is labor productivity (LP), and the independent variables are internet coverage (IC), digital skills (DS), and cloud adoption (CA). Robust standard errors are used to address potential heteroscedasticity issues.

$$\begin{aligned} &\text{LaborProductivity}\sqrt{\text{Digital Index}} \\ &= (\beta_0 + \beta_1\text{InternetCoverage} + \beta_2\text{DigitalSkills} + \beta_3\text{CloudAdoption} \\ &+\beta_4\text{Salary})\sqrt{\text{Digital Index}} + \epsilon\sqrt{\text{Digital Index}} \end{aligned} \quad (2)$$

Model 3 is a robust linear regression model without a control variable, where the dependent variable is Labor Productivity (LP), and the independent variables are internet coverage (IC), cloud adoption (CA), and digital skills (DS). Robust standard errors are used to address potential heteroscedasticity issues.

$$\text{LaborProductivity} = \beta_0 + \beta_1\text{InternetCoverage} + \beta_2\text{DigitalSkills} + \beta_3\text{CloudAdoption} + \epsilon \quad (3)$$

Model 4 is a robust linear regression model with the control variable (the natural logarithm of salary), where the dependent variable is labor productivity (LP), and the independent variables are internet coverage (IC), digital skills (DS), and cloud adoption (CA). Robust standard errors are used to address potential heteroscedasticity issues.

$$\text{LaborProductivity} = \beta_0 + \beta_1\text{InternetCoverage} + \beta_2\text{DigitalSkills} + \beta_3\text{CloudAdoption} + \beta_4\text{Salary} + \epsilon \quad (4)$$

Model 5 is a fixed-effects panel regression model, where the dependent variable is labor productivity (LP), and the independent variables are internet coverage (IC), digital skills (DS), and cloud adoption (CA). This model captures within-country variation and eliminates constant effects specific to each unit that could influence the relationship between variables.

$$\text{LaborProductivity}_{i,t} = \beta_0 + \beta_1\text{InternetCoverage}_{i,t} + \beta_2\text{DigitalSkills}_{i,t} + \beta_3\text{CloudAdoption}_{i,t} + \theta_i + \epsilon_{i,t} \quad (5)$$

where θ_i represents the fixed effects specific to each unit (country), i represents the country, and t represents the year.

Model 6 is a fixed-effects panel regression model, where the dependent variable is labor productivity (LP), and the independent variables are internet coverage (IC), digital skills (DS), and cloud adoption (CA). The natural logarithm of average salary (LN_SA) is used as a control variable, analyzing within-unit (country or region) variation and eliminating constant influences specific to each unit that could distort the relationships between variables.

$$\text{LaborProductivity}_{i,t} = \beta_0 + \beta_1\text{InternetCoverage}_{i,t} + \beta_2\text{DigitalSkills}_{i,t} + \beta_3\text{CloudAdoption}_{i,t} + \beta_4\text{Salary}_{i,t} + \theta_i + \epsilon_{i,t} \quad (6)$$

where θ_i represents the fixed effects specific to each unit (country), i represents the country, and t represents the year.

Compared to earlier studies [47–49] that examine how employees' digital skills influence both their performance and the adoption of Industry 4.0 technologies, this paper offers an original contribution by integrating an extended econometric framework that includes not only variables reflecting infrastructure (such as internet coverage and use of cloud technologies) but also those capturing employees' digital competencies. Unlike previous models, the study introduces a fixed-effects regression to capture national variations in labor productivity, alongside a comparative analysis across European Union member states. Furthermore, it contributes to a deeper understanding of the relationship between digital infrastructure, digital skills, and labor productivity in the context of Industry 4.0.

Table 1. Variable description.

Variable	Description	Unit of Measurement	Eurostat Code Source
Dependent Variable			
Labor Productivity (LP)	Gross domestic product at market prices	Current prices, million EUR	tec00001 [69]
	Total employment	Thousand persons	lfsi_emp_a [70]
Independent Variables			
Cloud Adoption (CA)	Cloud computing services	Percentage of enterprises	isoc_cicce_use [71]
Internet Coverage (IC)	Broadband internet coverage	Percentage of households	isoc_cbt [72]
Digital Skill (DS)	Individuals' level of digital skills	Percentage of individuals	isoc_sk_dskl_i [73], tepsr_sp410 [74]
Weighting Variable			
Digital Index (DI)	Enterprises with very high digital intensity index	Percentage of enterprises	isoc_e_dii [75]
Control Variable			
Salary (SA)	Average full-time adjusted salary per employee	EUR	nama_10_fte [76]

Descriptive statistics (Table 2) reveal substantial variability among the variables used in the regression analysis. The average salary (SA) variable, in particular, shows significant variation, with a mean of 29,336.09, a standard deviation of 16,656, and values ranging from 6374 to 81,064. This wide range justifies the application of a natural logarithmic (LN) transformation to stabilize the variance and address potential heteroscedasticity issues in the regression model.

Table 2. Descriptive statistics.

Statistics	LP	CA	IC	DS	DI	SA	LN_SA
N	243	170	243	161	213	234	234
Min	15.609	5,400	36.300	26.250	0.100	6374.000	8.759
Max	254.193	78.300	100.000	86.210	13.200	81,064.000	11.302
Mean	73.546	32.733	83.816	56.100	3.377	29,336.090	10.122
Std Dev	47.383	18.149	13.648	13.000	2.841	16,656.000	0.582
Skewness	1.652	0.620	−0.959	−0.014	1.452	0.763	−0.027
Kurtosis	6.036	2.438	3.471	2.951	4.578	2.643	2.009

The variance inflation factor (VIF) values indicate no significant multicollinearity among the analyzed variables. In the first model, VIF ranges from 1.21 to 1.94, while in the second model, it ranges from 1.19 to 2.07. Both results confirm that multicollinearity is not a concern. In the third model, VIF values span 1.39 to 2.05, and in the fourth model, they fall between 1.12 and 1.45, suggesting minimal collinearity among explanatory variables.

The Breusch–Pagan/Cook–Weisberg test for heteroscedasticity in Model 1 yields a value of 0.1202, exceeding the usual 0.05 threshold. This means there are no significant heteroscedasticity issues. The remaining models are robust or use fixed effects, which helps ensure the validity of the estimates. R-squared values for the six models range from 0.45 to 0.67, indicating that they explain 45% to 67% of the dependent variable's variation. The F-test probability is 0.0000 for all models, confirming they are statistically significant, and that the independent variables meaningfully account for changes in the dependent variable.

4. Results and Discussion

The first two models (1–2) use the digital index (DI) to weigh the variables, allowing us to examine how factors like internet coverage, digital skills, and cloud technology adoption influence productivity based on each country or region's overall level of digitalization. These weighted models show that digital factors impact productivity differently in economies with varying degrees of digitalization, providing a more nuanced understanding of the relationship between digitalization and productivity.

The robust models (3–4) and the panel models (5–6) highlight the crucial roles that digital skills (DS) and cloud adoption (CA) play in increasing labor productivity. Adding the control variable, the natural logarithm of average salary (LN_SA), enhances the models' ability to explain variations, emphasizing the connection between average salaries and digital factors. In contrast, the influence of internet coverage (IC) is less consistent and varies across different models. Panel Models 5–6 offer a more detailed perspective on local relationships, revealing significant differences between the countries analyzed.

The regression models have a different number of observations, because data for some variables are not available in all cases. Model 1 includes 88 observations, after excluding any that lacked values for all indicators. Data for 2016 and 2021 are available for all 27 EU countries. In 2017, there were 18 observations from Austria, Belgium, Bulgaria, Croatia, Cyprus, Czechia, Denmark, Finland, Greece, Hungary, Latvia, Lithuania, Poland, Portugal, Romania, Slovakia, Slovenia, and Spain. For 2015, data were available for the following 16 countries: Belgium, Bulgaria, Croatia, Cyprus, Denmark, Finland, Hungary, Ireland, Latvia, Lithuania, Malta, Poland, Romania, Slovakia, Slovenia, and Spain. Model 2 includes

85 observations. Compared to Model 1, data for Greece are missing for 2016, 2017, and 2021.

Models 3 and 5 use 116 observations. For 2015, there were 17 observations from Belgium, Bulgaria, Croatia, Cyprus, Denmark, Finland, Greece, Hungary, Ireland, Latvia, Lithuania, Malta, Poland, Romania, Slovakia, Slovenia, and Spain. Data are available for all 27 countries in 2016, 2021, and 2023. In 2017, there were 18 observations from Austria, Belgium, Bulgaria, Croatia, Cyprus, Czechia, Denmark, Finland, Greece, Hungary, Latvia, Lithuania, Poland, Portugal, Romania, Slovakia, Slovenia, and Spain. Models 4 and 6 include 111 observations. Compared to Models 3 and 5, data for Greece in 2015, 2016, 2017, 2021, and 2023 were not included.

The regression models in Table 3 show that internet coverage (IC) has a positive and significant effect in Models 1 and 2, confirming that digital infrastructure helps drive the adoption of Industry 4.0 technologies. Broad internet access makes it easier to use digital solutions, like IoT and cloud computing, which support process automation and lower operating costs. In Models 3 and 4, IC remains significant; although, its relative impact decreases once other factors (such as digital skills and average salary) are considered. This indicates that digital infrastructure is more of a facilitator than a direct driver of productivity. However, in the more complex Models 5 and 6, the coefficient for internet coverage (IC) becomes insignificant, suggesting that cross-country or regional differences outweigh internal factors.

Table 3. Coefficients of key variables across econometric models for labor productivity.

Variable	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
IC	0.736 (0.225) ***	0.747 (0.206) ***	0.738 (0.257) **	0.734 (0.270) **	0.051 (0.088)	−0.012 (0.119)
DS	1.481 (0.330) ***	1.072 (0.364) **	1.672 (0.384) ***	1.312 (0.401) ***	0.352 (0.1415) **	0.395 (0.138) **
CA	0.471 (0.220) **	0.309 (0.229)	0.295 (0.280)	0.132 (0.290)	0.596 (0.073) ***	0.466 (0.083) ***
LN_SA		18.135 (7.019) **		21.869 (6.380) ***		15.610 (6.102) **
Constant	−90.261 (22.176) ***	−244.227 (56.778) ***	−92.310 (28.730) ***	−287.436 (61.338) ***	26.758 (8.632) ***	−122.942 (56.547) **
Number of observation	88	85	116	111	116	111
R Square	0.55	0.60	0.45	0.51	0.63	0.67

*** $p < 0.01$, ** $p < 0.05$(standard errors are in parentheses). Dependent variable labor productivity (LP). Model 1: Linear robust regression OLS. Independent variables: internet coverage (IC), digital skills (DS), and cloud adoption (CA) weighted by the digital index (DI). Model 2: Linear robust regression OLS. Independent variables: internet coverage (IC), digital skills (DS), cloud adoption (CA), and average salary (LN_SA) weighted by the digital index (DI). Model 3: Linear robust regression OLS. Independent variables: internet coverage (IC), digital skills (DS), cloud adoption (CA), and average salary (LN_SA). Model 4: Linear robust regression OLS. Independent variables: internet coverage (IC), digital skills (DS), cloud adoption (CA), and average salary (LN_SA). Model 5: Fixed-effects panel regression. Independent variables: internet coverage (IC), digital skills (DS), and cloud adoption (CA). Model 6: Fixed-effects panel regression. Independent variables: internet coverage (IC), digital skills (DS), cloud adoption (CA), and average salary (LN_SA).

These findings only partially support Hypothesis H1, showing that, while digital infrastructure is essential for digitalization, it alone cannot guarantee long-term impact. This aligns with one study [9], which emphasizes that the benefits of internet access depend on coherent integration of advanced technologies and on public policies that reduce digital divides. The authors of [34] also underline the need to invest in digital infrastructure to narrow regional disparities, while the authors of [39] present examples from Asia, where steady investments have turned production sites into interconnected and dynamic systems.

Additionally, the authors of [13] emphasize that Industry 4.0 technologies not only increase productivity but also support sustainable economic development. They help reduce environmental impact and promote the efficient use of resources. These findings align with the observations of [1,32,33], who underline the role of digital infrastructure in transforming industry.

Moreover, some studies [2,3] highlight the importance of connectivity and the integration of IoT with big data for production optimization. The authors of [12] also show that the adoption of IoT, AI, and blockchain technologies boosts operational sustainability and enhances the productivity of industrial processes.

The analysis further shows that internet speed has a stronger effect on economies with higher digitalization (DI), though this impact diminishes when structural differences among countries come into play. These findings align with international studies, such as [31,59]. They show that a high-performing digital infrastructure directly contributes to operational efficiency. This highlights the need for policies that encourage digital infrastructure development in order to ease the adoption of advanced technologies, as also noted by [40,41].

Investments in digital infrastructure, including efforts to build employees' digital skills, need to be backed by suitable policies and strategies to positively influence labor productivity. One critical mechanism for doing so is government subsidies. Furthermore, professional training programs aligned with both market needs and technological demands, often developed in partnership with the business sector, can also play a key role in boosting labor productivity.

In all regression models from Table 3, the coefficient for digital skills (DS) is positive and significant, indicating a beneficial effect on labor productivity and supporting Hypothesis H2. Employees with advanced digital abilities have an edge in using Industry 4.0 technologies, which leads to streamlined processes, shorter production times, and greater work productivity. The authors of [5] reached similar conclusions, stressing the need for employees to have advanced digital skills. Other research [9] also highlights the role of digital competencies in safeguarding jobs against automation.

Based on the regression models, the digital skill (DS) variable exerts the strongest influence on labor productivity (LP). Its coefficient is higher in models without the control variable (Models 1 and 3) and then slightly declines in models that include the control variable (LN_SA) (Models 2 and 4). Adding the average salary control reduces the impact of digital skills on labor productivity.

In panel regression Models 5 and 6, which account for cross-country or regional differences, the coefficients for digital skill (DS) remain significant but are somewhat lower. This shows that the influence of digital skills persists across varied contexts. Digital skills are essential for developing a sustainable digital economy and play a major part in boosting labor productivity and narrowing labor market gaps.

These findings align with previous research. Some research [47,48] has identified the need for strategic training programs to equip the workforce for using new technologies. Observations by the authors of [49] underscore the importance of information literacy in adapting to Industry 4.0, a point further supported by other studies [37,38]. Meanwhile, the authors of [22] show that emerging economies investing in digital education have been more successful in capitalizing on the benefits of digitalization, while minimizing the risks of job automation.

Econometric analysis of the regression models confirms the importance of cloud technology adoption for labor productivity. In Model 1, the positive and significant coefficient for cloud adoption (CA) suggests that cloud technologies directly enhance labor productivity, especially in already digitalized economies. However, in Models 2 and 4, this effect becomes less pronounced, indicating that factors like average salary (LN_SA) can dampen the influence of cloud technologies. These results reflect the interdependence between technological infrastructure and the broader economic environment, as also pointed out by [5]. When fixed effects are applied in panel regression Models 5 and 6, constant differences among countries are removed, making the impact of cloud technologies on labor productivity even more evident. Prior studies support these findings. The authors of [58] argue that multi-cloud strategies and auto-scaling solutions enhance operational efficiency and cut costs. Some research [8] notes that cloud technologies reduce hardware needs and make it easier to adapt to market changes. Moreover, the authors of [57] emphasize that these technologies improve performance and widen service availability. In addition, other research [59], as well as [14,60], highlights the positive impact of cloud technologies on profitability and operational efficiency. Erumban's study [61] further reinforces this perspective by showing how digital investments help reduce costs. The econometric results, thus, confirm Hypothesis H3.

Overall, the findings show that digital infrastructure and workforce technology skills are crucial for implementing Industry 4.0, and that without them, labor productivity would be much lower. These elements are key to maintaining a high level of market competitiveness, as noted by [4,5]. Meanwhile, cloud-based IT solutions are important for streamlining industrial processes, as highlighted by [8]. This study demonstrates that all these factors strengthen a digitalized, competitive economy, aligning with existing research [31,34] and complemented by the perspectives outlined by the authors of [1].

The main challenges in implementing Industry 4.0 technologies include major disparities in digital infrastructure and technological capabilities among countries, which lead to economic and social inequalities. Another hurdle is resistance to change and lack of digital skills, with employees sometimes being skeptical about advanced technologies [9]. High initial costs for infrastructure, training, and technology also pose obstacles, particularly for SMEs, though tax incentives and government subsidies can help mitigate these issues [34]. These challenges are also highlighted by the studies of [6] and the European Commission report [30]. The transition to Industry 4.0 calls for investment in digital infrastructure, the development of digital skills, and measures that encourage the adoption of cloud technologies.

Companies and employees need time to adapt to new technologies, and the associated benefits emerge gradually. To see whether digitalization effects manifest with a delay, we estimated models that include lagged digitalization variables (internet coverage—IC and digital skill—DS), as shown in Table 4. This approach allowed us to explore whether digital infrastructure and digital skills have a long-term impact on productivity.

The results indicate that internet coverage plays a vital role in this transition. During the first two years after implementation (lag1, lag2), it exerts a significant effect on labor productivity. However, after three years (lag3), its impact begins to decline. Consequently, digital infrastructure must be complemented by additional measures to maintain a positive long-term influence.

Regarding digital skills, we did not observe a clear delayed effect. One possible reason is that these skills need ongoing updates to keep pace with emerging technologies. Without continuous training programs, the benefits may diminish over time. Digitalization generates the greatest gains in the short and medium term, yet sustained labor productivity growth requires steady investment in infrastructure, professional training, and innovation.

Table 4. Lagged effects table.

Variable	Lag 1	Lag 2	Lag 3	Lag 1	Lag 2	Lag 3	Lag 1	Lag 2	Lag 3
IC	0.766 (0.180) ***	0.838 (0.278) ***	0.641 (0.280) **	0.625 (0.281) **	0.922 (0.331) ***	0.590 (0.351)	0.009 (0.095)	0.123 (0.136)	0.330 (0.170) *
DS	1.033 (0.570) *	0.707 (0.752)	0.603 (1.122)	1.359 (0.562) **	1.408 (0.508) ***	1.470 (0.959)	0.1818 (0.139)	−0.061 (0.154)	0.095 (0.243)
CA	0.267 (0.302)	0.321 (0.383)	0.236 (0.554)	0.064 (0.395)	−0.041 (0.38)	−0.097 (0.604)	0.222 (0.083) ***	0.3226 (0.101) ***	0.097 (0.129)
LN_SA	14.403 (6.565) **	23.845 (10.123) **	22.304 (12.303) *	21.0340 (6.8613) ***	25.044 (7.454) ***	24.664 (12.178) **	5.605 (6.667)	22.360 (7.476) ***	−11.208 (13.471)
Constant	−204.291 (51.051) ***	−287.118 (81.929) ***	−244.148 (92.500) ***	−270.728 (61.223) ***	−331.181 (73.985) ***	−302.096 (102.531) ***	−6.994 (63.815)	−171.094 (69.684) **	151.087 (130.479)
Number of observation	94	69	51	94	95	51	94	95	51
R Square Variable	0.633	0.554	0.500	0.534	0.514	0.525	0.285	0.639	0.245

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$ (standard errors are in parentheses). Lag 1 (1 year), Lag 2 (2 years), and Lag 3 (3 years). Dependent variable labor productivity (LP). Model 2: Linear robust regression OLS. Independent variables: internet coverage (IC), digital skills (DS), cloud adoption (CA), and average salary (LN_SA) weighted by the digital index (DI). Model 4: Linear robust regression OLS. Independent variables: internet coverage (IC), digital skills (DS), cloud adoption (CA), and average salary (LN_SA). Model 6: Fixed-effects panel regression. Independent variables: internet coverage (IC), digital skills (DS), cloud adoption (CA), and average salary (LN_SA).

5. Conclusions

The specialized literature emphasizes the importance of digital infrastructure and professional skills in adopting Industry 4.0 technologies. By integrating the effects of digital infrastructure, technological skills, and cloud solutions on labor productivity within the European Union, this study expands the existing research through its findings. The results indicate that digital skills have a significant influence on labor productivity, while cloud solutions enhance operational efficiency, particularly in fixed-effects regression models.

The regression analyses reveal that digital skills (DS) exert a strong influence on labor productivity (LP) across all the models, underscoring the importance of human capital in adopting Industry 4.0 technologies. Cloud adoption (CA) has a significantly positive effect in the fixed-effects regression models (Model 5 and Model 6). Meanwhile, internet coverage (IC) is relevant in the robust regression models (Model 1–4) but not significant in the fixed-effects models. Although digital infrastructure is a key pillar in implementing Industry 4.0 technologies, it does not by itself determine labor productivity; instead, it must be considered alongside digital skills and technology investments.

Including the average salary (LN_SA) in Model 2, Model 4, and Model 6 indicates that wage levels reflect both the degree of digitalization and the adoption of advanced technologies. In turn, salary levels reinforce the impact of digital skills and cloud adoption on labor productivity, confirming the role of this variable as a control factor.

The results and conclusions we reached contribute to the specialized literature by highlighting how technological factors interact to shape labor productivity. They also emphasize the need for policies and professional training strategies that can help close regional gaps and support a sustainable transition toward the widespread adoption of Industry 4.0 technologies.

The implementation of Industry 4.0 technologies requires an approach that considers not only the modernization of digital infrastructure but also the development of the workforce's digital skills. Policies and strategies for adopting these technologies must be tailored to the specific economic development levels of each region or country. Digital competencies are very important, because they directly affect labor productivity, and in combination with cloud-based solutions, they significantly boost operational efficiency. The integrated approach to these factors helps narrow economic gaps and supports the transition to a more competitive economy.

Major contributions come from investments in high-speed internet expansion, support for cloud solutions, and professional training programs that build Industry 4.0 competencies. These investments are also crucial for closing gaps among countries, spurring faster development in less advanced regions. If supported by financial incentives and tax breaks, technological progress and the reduction in disparities can happen much more quickly. The results and conclusions presented here enable decision makers, managers, and public authorities to use these insights to successfully integrate new technologies aimed at boosting labor productivity. Additionally, investments in infrastructure and digital skills must be coupled with strategies that address structural shifts in the labor market, ensuring a fair and sustainable transition. Updating curricula and promoting continuous learning can help prevent technological unemployment and maintain competitiveness during periods of rapid change. A united European approach can lessen disparities among countries and promote the mobility of specialists, supporting more robust economic and social opportunities.

This study contributes significantly to our understanding of how digital infrastructure, technological competencies, and cloud solutions affect labor productivity.

The study's findings highlight the importance of digital infrastructure, technological skills, and information literacy in integrating Industry 4.0 technologies. Without a clear understanding of how to use these new technologies productively, investments in digital infrastructure and professional training may not deliver the desired improvements in labor productivity. Therefore, continuous training programs should include specific components dedicated to information literacy.

Beyond these factors, it is essential for all stakeholders, governments, companies, and educational institutions, to work together and adjust their strategies. This collaboration fosters robust digital ecosystems, where the skills and knowledge required for adopting Industry 4.0 technologies are accessible to everyone. As a result, digital transformation becomes not only an economic goal but also a real chance to ensure long-term prosperity and wellbeing.

This study drew on data from the European Union due to the notable differences in digitalization levels among its member states. On one hand, digitally advanced economies like Germany and the Netherlands coexist with nations in transition, such as Romania and Bulgaria. This diversity allows for a meaningful comparative analysis and explains significant variations in digital infrastructure, technological capabilities, and investments in digitalization. As a result, our sample captures not just regional disparities but also the interplay between Industry 4.0 technologies and each country's unique economic factors.

Investments in digital infrastructure and continuous workforce training are important for the successful adoption of advanced technologies. Well-designed policies can help narrow digital gaps and pave the way for an equitable shift to a knowledge-based economy. Consequently, these findings are relevant not only to the EU but also provide a framework for other economies facing similar challenges in their digitalization processes.

This study offers valuable insights into the role of digitalization in enhancing labor productivity, but it does have a few limitations. The data analyzed for the 2015–2023 period did not include values for all variables under examination. Moreover, the analyses were conducted solely for countries within the European Union.

Another potential limitation of our analysis is that the impact of digital transformation on labor productivity may not appear immediately. Both companies and employees require time to adapt to new technologies. To address this, we tested lagged models by introducing one-, two-, and three-year delays for indicators related to digital infrastructure and digital skills. The results show that, while internet coverage significantly influences productivity during the first two years, its effect diminishes thereafter.

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Appendix A

Table A1. Countries.

Countries		
Austria	France	Malta
Belgium	Germany	Netherlands
Bulgaria	Greece	Poland
Croatia	Hungary	Portugal
Cyprus	Ireland	Romania
Czechia	Italy	Slovakia
Denmark	Latvia	Slovenia
Estonia	Lithuania	Spain
Finland	Luxembourg	Sweden

References

1. Hermann, M.; Pentek, T.; Otto, B. Design Principles for Industrie 4.0 Scenarios. In Proceedings of the 2016 49th Hawaii International Conference on System Sciences (HICSS)—IEEE, Koloa, HI, USA, 5–8 January 2016; pp. 3928–3937.
2. Oztemel, E.; Gursev, S. Literature Review of Industry 4.0 and Related Technologies. *J. Intell. Manuf.* **2020**, *31*, 127–182. [CrossRef]
3. Sestino, A.; Prete, M.I.; Piper, L.; Guido, G. Internet of Things and Big Data as Enablers for Business Digitalization Strategies. *Technovation* **2020**, *98*, 102173. [CrossRef]
4. Schwab, K. *The Fourth Industrial Revolution*; Crown Business: New York, NY, USA, 2017; ISBN 978-1-5247-5887-5.
5. Brynjolfsson, E.; McAfee, A. *The Second Machine Age: Work, Progress, and Prosperity in a Time of Brilliant Technologies*; W.W. Norton & Co.: New York, NY, USA, 2014; p. 306, ISBN 978-0-393-23935-5.
6. Acemoglu, D.; Restrepo, P. Artificial Intelligence, Automation, and Work. In *The Economics of Artificial Intelligence: An Agenda*; University of Chicago Press: Chicago, IL, USA, 2018; pp. 197–236, ISBN 978-0-226-61333-8.
7. Eurostat Digital Economy and Society Statistics—Households and Individuals. Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Digital_economy_and_society_statistics_-_households_and_individuals (accessed on 7 December 2024).
8. Margherita, E.; Braccini, A.M. Industry 4.0 Technologies in Flexible Manufacturing for Sustainable Organizational Value: Reflections from a Multiple Case Study of Italian Manufacturers. *Inf. Syst. Front.* **2020**, *25*, 995–1016. [CrossRef]
9. Frey, C.B.; Osborne, M.A. The Future of Employment: How Susceptible Are Jobs to Computerisation? *Technol. Forecast. Soc. Change* **2017**, *114*, 254–280. [CrossRef]

10. McKinsey. Global Institute Notes from the AI Frontier: Modeling the Impact of AI on the World Economy. Available online: https://www.mckinsey.com/~/media/McKinsey/Featured%20Insights/Artificial%20Intelligence/Notes%20from%20the%20frontier%20Modeling%20the%20impact%20of%20AI%20on%20the%20world%20economy/MGI-Notes-from-the-AI-frontier-Modeling-the-impact-of-AI-on-the-world-economy-September-2018.ashx (accessed on 5 February 2025).
11. Nuruzzaman Abir, A.Z.M. Industry 4.0 Technologies for a Data-Driven, Secure, Green and Circular Manufacturing Economy. In Proceedings of the 2024 IEEE Green Technologies Conference (GreenTech), Springdale, AR, USA, 3–5 April 2024; pp. 26–31.
12. Chauhan, S.; Singh, R.; Gehlot, A.; Akram, S.V.; Twala, B.; Priyadarshi, N. Digitalization of Supply Chain Management with Industry 4.0 Enabling Technologies: A Sustainable Perspective. *Processes* **2023**, *11*, 96. [CrossRef]
13. Spaltini, M.; Poletti, A.; Acerbi, F.; Taisch, M. A Quantitative Framework for Industry 4.0 Enabled Circular Economy. *Procedia CIRP* **2021**, *98*, 115–120. [CrossRef]
14. Petcu, M.A.; Sobolevschi-David, M.-I.; Curea, S.C. Integrating Digital Technologies in Sustainability Accounting and Reporting: Perceptions of Professional Cloud Computing Users. *Electronics* **2024**, *13*, 2684. [CrossRef]
15. Relich, M. The Impact of ICT on Labor Productivity in the EU. *Inf. Technol. Dev.* **2017**, *23*, 706–722. [CrossRef]
16. Tutak, M.; Brodny, J. Business Digital Maturity in Europe and Its Implication for Open Innovation. *J. Open Innov. Technol. Mark. Complex.* **2022**, *8*, 27. [CrossRef]
17. European Commission. European Skills Agenda. Available online: https://employment-social-affairs.ec.europa.eu/policies-and-activities/skills-and-qualifications/european-skills-agenda_en (accessed on 7 December 2024).
18. European Commission. European Pillar of Social Rights—Building a Fairer and More Inclusive European Union. Available online: https://employment-social-affairs.ec.europa.eu/policies-and-activities/european-pillar-social-rights-building-fairer-and-more-inclusive-european-union_en (accessed on 3 February 2025).
19. European Commission. European Social Fund. Available online: https://european-social-fund-plus.ec.europa.eu/en (accessed on 7 December 2024).
20. Li, L. Reskilling and Upskilling the Future-Ready Workforce for Industry 4.0 and Beyond. *Inf. Syst. Front.* **2024**, *26*, 1697–1712. [CrossRef] [PubMed]
21. Spöttl, G.; Windelband, L. The 4th Industrial Revolution—Its Impact on Vocational Skills. *J. Educ. Work* **2021**, *34*, 29–52. [CrossRef]
22. Qin, S.; Liu, Z.; Wang, J.; Wu, Y. The Impact of Digital Transformation on Labour Demand Quantity and Structure: Evidence from China. *Econ. Anal. Policy* **2024**, *84*, 1452–1469. [CrossRef]
23. Becker, G.S. *Human Capital: A Theoretical and Empirical Analysis, with Special Reference to Education*, 3rd ed.; University of Chicago Press: Chicago, IL, USA, 1993; ISBN 978-0-226-04122-3.
24. Van Dijk, J.A.G.M. Digital Divide Research, Achievements and Shortcomings. *Poetics* **2006**, *34*, 221–235. [CrossRef]
25. Ferschli, B.; Rehm, M.; Schnetzer, M.; Zilian, S. Digitalization, Industry Concentration, and Productivity in Germany. *Jahrb. Natl. Stat.* **2021**, *241*, 623–665. [CrossRef]
26. Lee, J.-W.; Song, E.; Kwak, D.W. Aging Labor, ICT Capital, and Productivity in Japan and Korea. *J. Jpn. Int. Econ.* **2020**, *58*, 101095. [CrossRef]
27. Song, M.; Tao, W.; Shen, Z. The Impact of Digitalization on Labor Productivity Evolution: Evidence from China. *J. Hosp. Tour. Technol.* **2022**, *16*, 33–52. [CrossRef]
28. Voronkova, V.; Nikitenko, V.; Vasyl'chuk, G. Foreign Experience In Implementing Digital Education in The Context Of Digital Economy Transformation. *Balt. J. Econ. Stud.* **2023**, *9*, 56–65. [CrossRef]
29. Brodny, J.; Tutak, M. Digitalization of Small and Medium-Sized Enterprises and Economic Growth: Evidence for the EU-27 Countries. *J. Open Innov. Technol. Mark. Complex.* **2022**, *8*, 67. [CrossRef]
30. European Court of Auditors. *Digitising European Industry: An Ambitious Initiative Whose Success Depends on the Continued Commitment of the EU, Governments and Businesses, Special Report No 19/2020*; Publications Office of the European Union: Luxembourg, 2020.
31. OECD. *OECD Digital Economy Outlook 2020*; OECD Publishing: Paris, France, 2020.
32. Yadla, L.L.; Mudragada, R.A.; Poka, H.; Vignesh, T. Smart Manufacturing In Industries Using Internet Of Things. In Proceedings of the 2023 International Conference on Computer Communication and Informatics (ICCCI)—IEEE, Coimbatore, India, 23–25 January 2023; pp. 1–5.
33. Zaidi, S.M.R.; Alam, A.; Khan, M.Y. Enhancing Efficiency in Advanced Manufacturing through IoT Integration. *Eng. Headw.* **2024**, *11*, 55–61. [CrossRef]
34. McKinsey. *Global Institute Digital Manufacturing: Capturing Value and Resilience in Industry 4.0*; McKinsey & Company: New York, NY, USA, 2019.
35. Chen, S.; Liu, W.; Song, H. Broadband Internet, Firm Performance, and Worker Welfare: Evidence and Mechanism. *Econ. Inq.* **2020**, *58*, 1146–1166. [CrossRef]
36. Najarzadeh, R.; Rahimzadeh, F.; Reed, M. Does the Internet Increase Labor Productivity? Evidence from a Cross-Country Dynamic Panel. *J. Policy Model.* **2014**, *36*, 986–993. [CrossRef]

37. Hsieh, E.W.-T.; Goel, R.K. Internet Use and Labor Productivity Growth: Recent Evidence from the U.S. and Other OECD Countries. *NETNOMICS Econ. Res. Electron. Netw.* **2019**, *20*, 195–210. [CrossRef]
38. Varlamova, J.; Larionova, N. Labor Productivity in the Digital Era: A Spatial-Temporal Analysis. *Int. J. Technol.* **2020**, *11*, 1191–1200. [CrossRef]
39. Kim, J.; Abe, M.; Valente, F. Impacts of the Digital Economy on Manufacturing in Emerging Asia. *Asian J. Innov. Policy* **2019**, *8*, 1–30. [CrossRef]
40. Tripathy, L.K.; Biswal, L.; Nikam, R.; Karekar, P. An Analytic Study of The Relationship Between Internet Connectivity and Productivity in The Workplace. *J. Inform. Educ. Res.* **2024**, *4*, 776–783. [CrossRef]
41. Viollaz, M. Information and Communication Technology Adoption in Micro and Small Firms: Can Internet Access Improve Labour Productivity? *Dev. Policy Rev.* **2019**, *37*, 692–715. [CrossRef]
42. Romer, P.M. Endogenous Technological Change. *J. Polit. Econ.* **1990**, *98*, S71–S102. [CrossRef]
43. Czernich, N.; Falck, O.; Kretschmer, T.; Woessmann, L. Broadband Infrastructure and Economic Growth. *Econ. J.* **2011**, *121*, 505–532. [CrossRef]
44. Gallardo, R.; Whitacre, B.; Kumar, I.; Upendram, S. Broadband Metrics and Job Productivity: A Look at County-Level Data. *Ann. Reg. Sci.* **2021**, *66*, 161–184. [CrossRef]
45. Hagsten, E. Broadband Connected Employees and Labour Productivity: A Comparative Analysis of 14 European Countries Based on Distributed Microdata Access. *Econ. Innov. New Technol.* **2016**, *25*, 613–629. [CrossRef]
46. Christensen, C. *The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail*; Harvard Business School Press: Boston, MA, USA, 1997.
47. Vuorikari, R.; Kluzer, S.; Punie, Y. *DigComp 2.2: The Digital Competence Framework for Citizens—With New Examples of Knowledge, Skills and Attitudes*; Publications Office of the European Union: Luxembourg, 2022.
48. Antonazzo, L.; Stroud, D.; Weinel, M. Institutional Complementarities and Technological Transformation: IVET Responsiveness to Industry 4.0—Meeting Emerging Skill Needs in the European Steel Industry. *Econ. Ind. Democr.* **2023**, *44*, 25–46. [CrossRef]
49. Yaacob, T.Z.; Poobalan, K.; Hashim, H.I.C.; Hasan, M.Z.; Subramaniam, Y.; Indiran, L. The Relationship Between Students' Digital Competency Skills and Adaptation to Industry 4.0 Learning Technologies. *Int. J. Acad. Res. Bus. Soc. Sci.* **2024**, *14*, 622–632. [CrossRef] [PubMed]
50. Assante, D.; Caforio, A.; Flamini, M.; Romano, E. Smart Education in the Context of Industry 4.0. In Proceedings of the 2019 IEEE Global Engineering Education Conference (EDUCON)—IEEE, Dubai, United Arab Emirates, 8–11 April 2019; pp. 1140–1145.
51. Siregar, K.E.; Akhter, N. Digital Leadership in the Era of Industry 4.0: A Comprehensive Literature Review. *Int. J. Educ. Eval. Policy Anal.* **2024**, *1*, 30–41. [CrossRef]
52. Kozanoglu, D.C.; Abedin, B. Understanding the Role of Employees in Digital Transformation: Conceptualization of Digital Literacy of Employees as a Multi-Dimensional Organizational Affordance. *J. Enterp. Inf. Manag.* **2020**, *34*, 1649–1672. [CrossRef]
53. Cardoso, A.; Pereira, M.S.; Sá, J.C.; Powell, D.J.; Faria, S.; Magalhães, M. Digital Culture, Knowledge, and Commitment to Digital Transformation and Its Impact on the Competitiveness of Portuguese Organizations. *Adm. Sci.* **2024**, *14*, 8. [CrossRef]
54. Cirillo, V.; Fanti, L.; Mina, A.; Ricci, A. The Adoption of Digital Technologies: Investment, Skills, Work Organisation. *Struct. Chang. Econ. Dyn.* **2023**, *66*, 89–105. [CrossRef]
55. Liao, L.; Du, M. How Digital Finance Shapes Residents' Health: Evidence from China. *China Econ. Rev.* **2024**, *87*, 102246. [CrossRef]
56. Teece, D.J.; Pisano, G.; Shuen, A. Dynamic Capabilities and Strategic Management. *Strateg. Manag. J.* **1997**, *18*, 509–533. [CrossRef]
57. Gupta, S.; Meissonier, R.; Drave, V.A.; Roubaud, D. Examining the Impact of Cloud ERP on Sustainable Performance: A Dynamic Capability View. *Int. J. Inf. Manag.* **2020**, *51*, 102028. [CrossRef]
58. Reznikov, R. The Economic Impact of Cloud Technologies on the Industry 4.0 Development. *Econ. Her. Donbas* **2023**, *74*, 67–74. [CrossRef]
59. Chen, X.; Guo, M.; Shangguan, W. Estimating the Impact of Cloud Computing on Firm Performance: An Empirical Investigation of Listed Firms. *Inf. Manag.* **2022**, *59*, 103603. [CrossRef]
60. Zhu, M.; Liang, C.; Yeung, A.C.L.; Zhou, H. The Impact of Intelligent Manufacturing on Labor Productivity: An Empirical Analysis of Chinese Listed Manufacturing Companies. *Int. J. Prod. Econ.* **2024**, *267*, 109070. [CrossRef]
61. Erumban, A.A. Informality and Aggregate Labor Productivity Growth: Does ICT Moderate the Relationship? *Telecommun. Policy* **2024**, *48*, 102681. [CrossRef]
62. Williamson, O.E. The Economics of Organization: The Transaction Cost Approach. *Am. J. Sociol.* **1981**, *87*, 548–577. [CrossRef]
63. Coase, R.H. The Nature of the Firm. *Economica* **1937**, *4*, 386–405. [CrossRef]
64. Rogers, E. *Diffusion of Innovations*, 3rd ed.; Free Press: New York, NY, USA, 1983; ISBN 978-0-02-926650-0.
65. Wooldridge, J.M. *Econometric Analysis of Cross Section and Panel Data*, 2nd ed.; MIT Press: Cambridge, MA, USA, 2010; ISBN 978-0-262-29679-3.
66. Huber, P.J. Robust Estimation of a Location Parameter. *Ann. Math. Stat.* **1964**, *35*, 73–101. [CrossRef]

67. Baltagi, B.H. *Econometric Analysis of Panel Data*; Springer Texts in Business and Economics; Springer International Publishing: Cham, Switzerland, 2021; ISBN 978-3-030-53952-8.
68. Arellano, M. *Panel Data Econometrics*; Oxford University Press: Oxford, UK, 2003; ISBN 978-0-19-924528-4.
69. Eurostat. Gross Domestic Product at Market Prices. Available online: https://ec.europa.eu/eurostat/databrowser/product/page/TEC00001 (accessed on 3 January 2025).
70. Eurostat. Employment and Activity. Available online: https://ec.europa.eu/eurostat/databrowser/product/page/LFSI_EMP_A (accessed on 3 January 2025).
71. Eurostat. Cloud Computing Services. Available online: https://ec.europa.eu/eurostat/databrowser/product/page/ISOC_CICCE_USE (accessed on 3 January 2025).
72. Eurostat. Broadband Internet Coverage by Technology. Available online: https://ec.europa.eu/eurostat/databrowser/product/page/ISOC_CBT (accessed on 3 January 2025).
73. Eurostat. Individuals' Level of Digital Skills. Available online: https://ec.europa.eu/eurostat/databrowser/product/page/ISOC_SK_DSKL_I (accessed on 3 January 2025).
74. Eurostat. Individuals Who Have Basic or Above Basic Overall Digital Skills. Available online: https://ec.europa.eu/eurostat/databrowser/product/page/TEPSR_SP410 (accessed on 3 January 2025).
75. Eurostat. Digital Intensity. Available online: https://ec.europa.eu/eurostat/databrowser/product/page/ISOC_E_DII (accessed on 3 January 2025).
76. Eurostat. Average Full Time Adjusted Salary per Employee. Available online: https://ec.europa.eu/eurostat/databrowser/product/page/NAMA_10_FTE (accessed on 3 January 2025).