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Information and Communication Technology, and Supply Chains as Economic Drivers in the European Union

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Abstract: *Background*: The adoption of information and communication technology (ICT) is transforming supply chains in the European Union, affecting logistical performance, economic integration and sustainability. This study examines the extent to which ICT adoption affects logistics efficiency in the 27 EU Member States. *Methods*: Using panel data from the World Bank and UNCTAD (2008–2018), the analysis applies the Arellano–Bond Generalized Method of Moments estimator to assess the impact of ICT indicators, broadband penetration, mobile connectivity and digital skills on logistics performance. GDP per capita and trade openness are included as control variables. *Results*: The results show that a 1% increase in ICT usage correlates with a 0.12-point increase in the Logistics Performance Index. Higher ICT usage leads to more efficient supply chains, lower costs and higher customer satisfaction. However, there are still differences in digitalization: the ICT usage rate of SMEs is 28% in Bulgaria and 27% in Romania, compared to the EU average of 59%. *Conclusions*: Bridging the digital divide requires targeted investments in ICT infrastructure, harmonized regulatory frameworks and stronger public–private cooperation to foster regional economic cohesion. This study provides policy recommendations to drive digital transformation, strengthen the resilience of logistics and improve the sustainability of supply chains in the EU.

Keywords: ICT integration; digital economy; digital technologies; sustainability of e-commerce; supply chain dynamics; sustainable supply chains; e-commerce social impact

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1. Introduction

The European Union has undergone a significant transformation in its e-commerce and logistics landscape over the last decade, driven primarily by advances in information and communication technology. Digitalization has reshaped supply chains by improving efficiency, promoting economic integration and increasing responsiveness to market demands. As companies adapt to changing consumer expectations that demand speed, sustainability and resilience, technologies such as big data analytics, the Internet of Things, artificial intelligence and blockchain have become indispensable tools for optimizing supply chains. These solutions enable real-time tracking, smarter inventory management, fewer logistical inefficiencies and more sustainable business practices.

Despite these benefits, the use of ICT remains uneven across EU member states, with significant differences between the leading economies and those in Central and Eastern Europe. While digitally advanced nations have successfully used ICT to improve logistics and strengthen economic ties, differences in infrastructure and digital capabilities have hindered progress in other regions. These inequalities affect the scalability of ICT-related

benefits and raise critical questions about the overall impact of digital transformation on economic performance, sustainability and regional cohesion. Addressing these inequalities requires targeted policies and investments that ensure equitable access to digital tools and technologies.

ICT plays a central role in modernizing supply chains by improving transparency, collaboration and customer service. Research has demonstrated their positive impact on logistics efficiency, supply chain resilience and trade facilitation, but there are few comprehensive studies that address the environmental and social impacts. Much of the existing literature focuses on cost reductions and operational efficiency and often overlooks how ICT contributes to sustainability, carbon footprint reduction and the circular economy. Moreover, the relationship between ICT adoption, regional supply chain integration and long-term economic stability remains under-researched, leaving crucial gaps in understanding the impact of digital transformation on macroeconomic stability and trade dynamics in the EU.

This study examines the impact of ICT adoption on logistics performance, supply chain integration and economic sustainability in EU Member States. Using econometric analysis, including the Arellano–Bond Generalized Method of Moments approach, the study examines the role of ICT access, ICT infrastructure and ICT usage in increasing logistics efficiency, while addressing potential endogeneity issues using panel data methods. The study also assesses the suitability of different estimation techniques, including fixed and random effects models, to check the robustness of the results.

By providing empirical evidence on the role of digital advancement in shaping supply chain dynamics, this study emphasizes the economic and environmental impact of ICT adoption. It not only assesses the impact of digitalization on logistics performance, but also examines the challenges and opportunities associated with ICT integration. The findings contribute to the ongoing discussion on how digital transformation can improve competitiveness, promote sustainability and support a more integrated and resilient European supply chain network.

The remainder of this paper is organized as follows. The next section reviews the existing literature on ICT, supply chains and economic development. This is followed by a discussion of the data and methodology, explaining the panel data techniques used. The empirical results are then presented and analyzed, leading to a discussion of the key findings. The final section highlights the policy implications of the study and outlines future research directions. It concludes with a reflection on the overall significance of digital transformation for supply chain management and economic integration in the EU.

2. Literature Review

The role of information and communication technology (ICT) in supply chain management and economic development has increased significantly over the last two decades. Digital innovations have improved efficiency, transparency and coordination in supply chains and influenced both global and regional trade networks. Technologies such as cloud computing, artificial intelligence (AI), blockchain and the Internet of Things (IoT) have become central to logistics and have improved processes from procurement to distribution. These tools help to reduce costs, improve decision making and strengthen competitiveness, while supporting economic integration within the European Union (EU).

To assess the impact of ICT on supply chains and economic development, a literature search was conducted using the Web of Science Core Collection. A search for supply chains, economy, ICT and e-commerce resulted in 655 relevant studies. Research in this area has increased significantly since 2004, with a sharp rise after 2014, reflecting the growing interest in how digitalization affects logistics and trade. Existing studies confirm that ICT

improves real-time data sharing, predictive analytics and automation, leading to better forecasting, reduced inefficiencies and improved inventory control. Figure 1 shows the time distribution and the increasing number of publications citing supply chains and ICT in economic development.

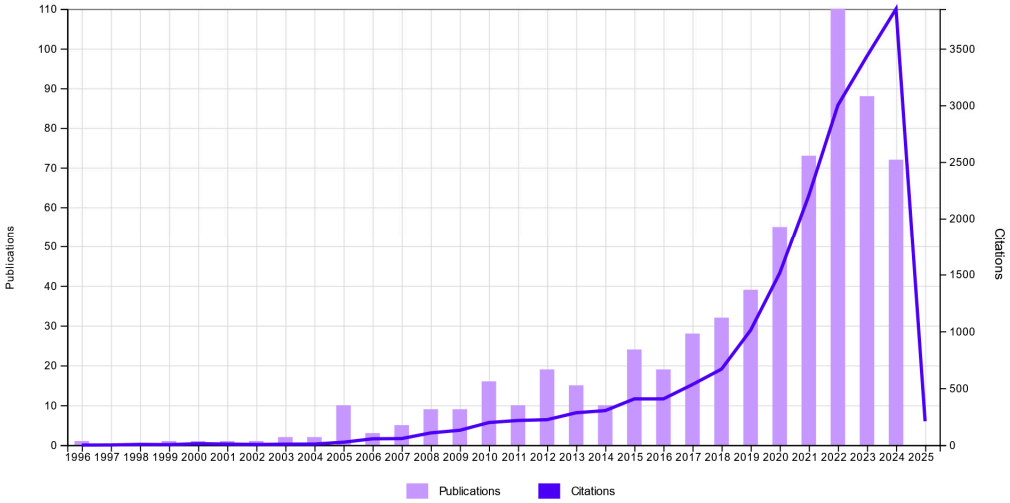


Figure 1. Time distribution of the number of publications and citations for the fields of supply chain and ICT in economic development. Source: Created by the authors using WoS web service.

Keyword analysis identified predominant themes, with key terms such as supply chain, industry, technology and product frequently appearing alongside research topics on firms, countries and companies. Based on titles, abstracts and keywords, a heat map (Figure 2) was created to illustrate the primary research focus areas.

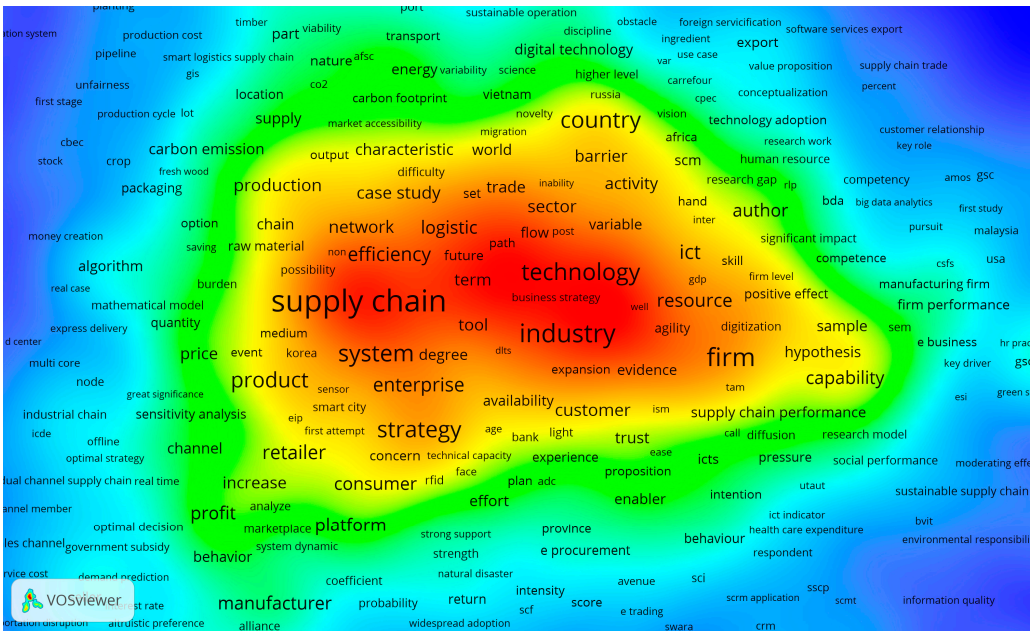


Figure 2. Heat map of keywords based on the analysis of titles, abstracts and keywords. Warmer colors at the center indicate more common use of the keyword. Source: Authors (analysis performed using VOSviewer software ver. 1.6.20).

Most of the publications analyzed come from the fields of management (169), operations research and management science (91) and business (89). Identifying relevant subject

areas is essential to ensure a focused review of the literature within the same field while recognizing the contributions of qualified researchers.

While the analysis confirmed a wide range of research, it also revealed a critical gap in studies examining value chains between EU Member States within macroeconomic systems. This gap underlines the importance of further research on ICT-enabled supply chain integration in the European Union. The introduction of information and communication technology (ICT) has profoundly changed the management of supply chains, improving efficiency, transparency and sustainability. Technologies such as RFID, IoT and blockchain have streamlined operations by enabling real-time communication, optimized inventory control and improved tracking capabilities.

ICT also plays a role in economic growth and trade integration within the EU. However, differences in digital infrastructure and uptake across Member States lead to unequal access to these benefits, impacting supply chain performance. Recent research has also explored the contribution of ICT to sustainability, particularly in the areas of green logistics, emissions reduction and circular economy models. Technologies such as AI-powered route planning and blockchain-powered traceability are being developed to make supply chains more sustainable and resource efficient.

Despite this progress, there are still significant barriers. Implementation costs, cybersecurity risks, regulatory differences and a lack of digital skills pose a challenge, especially for small and medium-sized enterprises (SMEs). While studies have examined the role of ICT in specific industries and national contexts, a more comprehensive assessment of its impact on supply chains across the EU is still lacking. The links between ICT adoption, economic integration and logistics performance, particularly in terms of sustainability and regional development, have not yet been fully explored.

Wamba et al. [1] have shown that RFID technology and the EPC network significantly improve logistics in mobile B2B commerce, optimize processes and increase efficiency. Mathaba et al. [2] investigated the role of IoT and Web 2.0 in improving inventory management, facilitating real-time tracking and supporting green logistics. Allaoui et al. [3] examined the complexity of the supply chain and emphasized the importance of balancing economic, environmental and social factors. They emphasized the importance of decision support systems for sustainable operations and highlighted the role of ICT in multi-party collaboration and long-term planning.

Arvin et al. [4] analyzed the growing interdependence between digital platforms and global supply chains and concluded that ICT and trade drive economic expansion, but that further empirical validation of causal relationships is needed. Ceynowa et al. [5] showed that ICT increases business sustainability, strengthens competitiveness, improves B2B communication and facilitates real-time decision making. Debnath and Sarkar [6] examined supply chain sustainability through the lens of circular economy principles and showed how ICT helps in waste management by supporting the framework of Reduce, Reuse and Recycle.

Garcia-Alcaraz et al. [7] quantified the impact of ICT on supply chains and showed its positive effect on key performance indicators, including cost efficiency and operational flexibility. Kim and Kim [8] analyzed sustainable supply chain trends and companies' adaptation strategies, while Luthra et al. [9] showed how effective information systems improve customer service, resource allocation, and overall economic and environmental sustainability. Mendoza-Fong et al. [10] investigated the role of ICT in green supply chains and found indirect benefits for sustainability. Paraskevas et al. [11] explored ICT-enabled approaches to smart logistics, while Pineda et al. [12] examined the broader implications for the digital transformation of the economy and technological innovation.

Poppe et al. [13] examined the integration of ICT into agri-food supply chains and found that it can improve efficiency despite existing gaps in coordination between actors. Shiralkar et al. [14] assessed supply chain disruptions and concluded that ICT improves resilience by highlighting vulnerabilities and supporting proactive strategies. Singh et al. [15] analyzed the contribution of ICT to the competitiveness of SMEs and showed how digital tools promote sustainable growth in the food sector. Song et al. [16] investigated how big data bridge the gap between economic development and environmental sustainability and enable informed decision making in resource management.

Sustainability has become a key issue in logistics, especially in the context of policies such as the EU Green Deal. ICT promotes sustainable practices in the supply chain through energy-efficient warehousing, environmentally friendly packaging and optimized transport networks. Martí et al. [17] confirmed the link between ICT-enabled logistics performance and international trade and emphasized the role of ICT in improving customs efficiency, infrastructure quality and supply chain transparency.

Mance et al. [18] examined the impact of ICT on regional supply chains, particularly in Central and Eastern European countries, and showed that ICT has the potential to strengthen economic integration despite infrastructural constraints. Their analysis of Croatian export value chains [19] emphasized the role of ICT in improving trade transparency, reducing transaction costs and increasing competitiveness. Zhang and Shang [20] investigated optimal supply chain strategies for e-commerce platforms, focusing on low-carbon product preferences. Momena et al. [21] utilized multi-criteria decision making to evaluate supply chain bottlenecks for e-commerce retailers. Magableh et al. [22] explored the intersection of blockchain, big data analytics and business model innovation, emphasizing their role in adapting to market uncertainty.

Despite progress, there are still significant ICT disparities in the EU that affect logistics performance and economic cohesion. In Bulgaria, only 28% of SMEs had basic digital equipment in 2023, compared to the EU average of 59%, limiting their ability to integrate digital logistics solutions [23]. Similarly, only 27% of Romanian SMEs had basic digital skills, limiting IoT-enabled fleet management [24]. Structural gaps in ICT employment illustrate the uneven digital transformation. In Poland, the share of ICT employees in total employment in 2023 is 4.3%, slightly below the EU average of 4.8%, which is hampering AI-driven logistics innovation [25]. In Greece (2.4%) and Romania (2.6%), the differences are even more pronounced and give cause for concern about long-term competitiveness, while Sweden is at the top with 8.7% [26]. Eliminating these imbalances requires investment in broadband infrastructure, the development of digital skills and harmonization of legislation. Without decisive action, there is a risk that the less digitally advanced member states will fall further behind and regional economic integration will be weakened.

Digitalization is transforming logistics, with broadband access playing a key role in efficiency and connectivity [27]. A strong digital infrastructure facilitates trade and logistics, even if cost reduction depends on its implementation [27]. However, inequalities between urban and rural areas continue to hinder the adoption of ICT and slow down the diffusion of digital location technologies [28]. In emerging markets, ICT improves supply chain resilience through optimized route planning and real-time tracking [29]. Digital progress remains uneven across EU Member States, with higher ICT penetration associated with better logistics performance, while lower penetration contributes to inefficiencies [30]. To close these gaps, targeted policy interventions are needed to accelerate ICT integration across all sectors [30]. From a sustainability perspective, digitalization improves supply chain transparency, reduces emissions and promotes resource efficiency [31].

The Internet of Things (IoT) has revolutionized supply chain management by enabling real-time data acquisition, facilitating continuous monitoring of goods and assets through-

out the supply chain. IoT sensors, RFID tags, and GPS tracking devices allow businesses to monitor the status and location of shipments, ensuring greater transparency and control over logistics operations. This capability enhances inventory management, reduces losses, and improves overall supply chain efficiency by minimizing stockouts, overstocking, and disruptions [32].

Artificial intelligence (AI) plays a crucial role in logistics optimization by integrating machine learning, optimization algorithms, and real-time data analytics. AI improves route planning, warehouse automation, and supply chain decision making, enabling businesses to optimize costs, efficiency, and sustainability. Recent research highlights AI's ability to enhance transport planning, reduce waste, and minimize carbon footprints in supply chain operations [33].

The integration of blockchain technology with IoT devices offers significant improvements in supply chain management by enhancing transparency, security, and traceability. This combination addresses challenges such as lack of visibility, flexibility, and risk management in supply chains. A comprehensive review explores the potential of blockchain-based IoT devices in revolutionizing supply chain management [34].

The IoT and social media provide information related to disasters that could help businesses strategically mitigate risks and optimize their supply chain during difficult times. A proposed framework shows how businesses can collaborate with communities and governments in disaster supply chain risk management [35].

The IoT and its benefits and challenges are emergent research topics among academics and practitioners. With supply chains gaining rapid complexity, having high supply chain visibility helps companies ease processes and reduce complexity by improving inaccuracies. A study highlights the role of IoT in enhancing supply chain visibility [36].

Overall, ICT remains a fundamental driver of supply chain efficiency, collaboration and sustainability. However, the broader impact of digital transformation on logistics systems has not yet been sufficiently researched. Most studies focus on isolated technologies or specific regions, leaving gaps in understanding how ICT, sustainability and logistics performance interact in different economic contexts. This study fills these gaps by using panel data analysis to provide a comprehensive assessment of the role of ICT in sustainable supply chains in EU Member States.

3. Data and Methods

This study uses a balanced panel dataset covering 27 EU Member States from 2011 to 2019, sourced from the World Bank, Eurostat and the European Commission's Digital Economy and Society Index (DESI) [30]. The dataset captures key variables related to ICT adoption, logistics performance and economic sustainability, thus ensuring analytical consistency. The dependent variable, the Logistics Performance Index (LPI) published by the World Bank, measures logistics efficiency on a scale of 1 to 5 across six dimensions: customs efficiency, infrastructure quality, international transportation, logistics expertise, tracking and tracing, and timeliness. The LPI, which is calculated as a weighted average of these components, has been continuously refined since its introduction in 2007. The 2018 update improved the reliability of the data while maintaining consistency for longitudinal analysis. In this study, the LPI assesses logistics efficiency in EU Member States, while ICT indicators, such as broadband penetration, digital infrastructure and e-commerce integration, are analyzed for their impact on supply chain performance. This enables an empirical assessment of the role of ICT in logistics, cost efficiency and regional trade integration.

Independent variables representing ICT use include broadband penetration, mobile internet connectivity and a digital skills index reflecting both infrastructure and work-

force adaptability. Broadband penetration improves real-time communication, accelerates data exchange and supports cloud-based supply chain management. Mobile connectivity enables GPS and IoT-based shipment tracking, logistics coordination and mobile inventory management. The digital skills index reflects the adaptability of the workforce to digital tools, reduces human error and enables AI-driven logistics solutions. ICT infrastructure (ICTINFR) strengthens cybersecurity, streamlines cross-border trade and improves the resilience of logistics networks, while ICT access (ICTACC) supports the adoption of e-commerce, increases supply chain visibility and facilitates automated inventory management. ICT utilization (ICTUSE) promotes predictive analytics, robotic processes and supply chain visibility using blockchain. Together, these indicators contribute significantly to logistical efficiency, cost reduction and supply chain sustainability.

QoS-Aware Software-Defined IoT (QoS-SD-IoT) increases network efficiency by intelligently allocating resources and ensuring low-latency, high-priority data transmission for critical logistics operations such as automated port management, supply chain analysis and real-time shipment tracking. As the EU relies on multimodal logistics networks, QoS-SD-IoT strengthens cross-border trade by ensuring a stable and reliable flow of data between transportation systems, customs platforms and warehouse management centers. In addition, Load-Balanced SD-IoT prevents congestion in AI-driven fleet management, real-time tracking and predictive logistics analytics by distributing network traffic more effectively. In an EU landscape where, digital infrastructure varies from region to region, this technology plays a key role in bridging the digital divide and ensuring consistent logistics network performance. The integration of edge computing further enhances SD-IoT by moving data processing closer to logistics hubs, reducing reliance on centralized cloud infrastructure and enabling faster, real-time decisions.

Table 1 summarizes the impact of these ICT indicators on supply chain optimization.

Table 1. Impact of ICT indicators on supply chain optimization.

ICT Indicator	Key Function	Impact on Supply Chain Efficiency
Broadband Penetration	High-speed communication	Reduced delays
Mobile Internet Connectivity	Real-time logistics tracking	Improved shipment monitoring
Digital Skills Index	Workforce adaptability	Reduced human error
ICT Infrastructure	Data centers, cybersecurity	Secure and resilient logistics
ICT Access	Availability of ICT services	Greater e-commerce integration
ICT Usage	Adoption of digital tools	Enhanced automation and analytics

To control for other factors that affect logistics performance, the dataset includes GDP per capita, trade openness (imports and exports as a percentage of GDP), foreign direct investment inflows and indicators of institutional quality such as governance efficiency and regulatory quality. The panel dataset comprises 243 observations, which ensures a robust cross-sectional and longitudinal analysis. Missing values were considered by multiple imputation techniques, so that the integrity of the dataset is maintained and distortions are avoided at the same time.

This study uses a balanced panel dataset covering 27 EU Member States from 2011 to 2019. Data sources include the World Bank, Eurostat and the European Commission's Digital Economy and Society Index (DESI) [30]. The dependent variable is the Logistics Performance Index (LPI), which measures customs efficiency, infrastructure quality, shipment tracking and punctuality. The independent variables include broadband penetration, mobile internet connectivity and a digital skills index representing ICT adoption. Control variables such as GDP per capita, trade openness (imports and exports as a percentage of

GDP), foreign direct investment inflows, institutional quality metrics and energy consumption indicators are also included.

Diagnostic tests ensure the reliability of the data. The Breusch–Pagan LM and Pesaran CD tests address cross-sectional dependence, while the delta test assesses the homogeneity of the slope coefficients between member states. To confirm the stationarity of the variables and avoid spurious regressions, the CIPS unit root test is applied.

The correlation matrix shown in Table 2 was created to examine possible multicollinearity between the most important variables in this study: Logistics Performance Index (LPI), ICT infrastructure (ICTINFR), ICT access (ICTACC), ICT utilization (ICTUSE) and GDP per capita in PPP (GDPPCPPP). By analyzing the relationships between these variables, we aim to assess whether high correlations indicate redundancy or overlapping explanatory power, which could affect the reliability of the regression results. This step is crucial to ensure the robustness of the econometric analysis.

Table 2. Correlation matrix of the most important variables.

	LPI	ICTINFR	ICTACC	ICTUSE	INTERNET	GDPPCPPP
LPI	1.0000					
ICTINFR	0.1808	1.0000				
ICTACC	0.1415	0.7801	1.0000			
ICTUSE	0.1402	0.8616	0.7971	1.0000		
INTERNET	0.2280	0.7400	0.7739	0.8085	1.0000	
GDPPCPPP	0.0184	0.5363	0.7383	0.6473	0.6850	1.0000

Data source: UNCTAD-Eora database and World Bank. Calculation: EViews 13. Sample: 2011–2019.

The correlation matrix in Table 2 indicates a potential for multicollinearity between some variables, particularly within the ICT-related variables. Strong correlations are observed between ICT infrastructure (ICTINFR) and ICT access (ICTACC) at 0.78 and between ICTINFR and ICT use (ICTUSE) at 0.86. ICTACC and ICTUSE also show a strong correlation of 0.79. These correlations indicate an overlapping explanatory power of the ICT variables, which could lead to multicollinearity problems in the regression models.

Since ICT usage (ICTUSE) often best reflects the real-world adoption and integration of technology, it is the most meaningful variable for examining its impact on logistics performance and economic outcomes. The selection of ICTUSE minimizes the redundancy created by the strong correlations between the ICT variables, as can be seen in the correlation matrix. To ensure the robustness of the regression analysis, VIF (Variance Inflation Factor) tests are used to detect any remaining multicollinearity. If multicollinearity persists, advanced dimensionality reduction techniques such as principal component analysis (PCA) can be used to extract independent components to ensure the reliability of the econometric results and the validity of the conclusions drawn from the analysis.

Table 3 summarizes the descriptive statistics of the main variables of the study, including the Logistics Performance Index (LPI), ICT infrastructure (ICTINFR), ICT access (ICTACC), ICT usage (ICT_USE) and GDP per capita (GDPPCPPP).

The mean values show that the LPI averages 3.515, indicating moderate logistics performance in the EU countries, while GDP per capita shows considerable variation, ranging from 15.661 EUR to 121.292 EUR with a mean value of EUR 39.146. The ICT variables show relatively high average values, with ICTINFR, ICTACC and ICTUSE reflecting a high level of ICT integration, but varying widely as their standard deviations show. The values for skewness and kurtosis indicate that GDP per capita has a highly skewed and leptokurtic distribution, while other variables have a distribution closer to normal. These descriptive results form the basis for further econometric analysis to ensure that variability and distributional characteristics are adequately accounted for.

Table 3. Descriptive statistics of the most important variables.

	LPI	ICTINFR	ICTACC	ICTUSE	INTERNET	GDPPCPPP
Mean	3.5154	64.5141	75.4811	58.3236	77.5908	39,146.9
Median	3.5100	64.4000	75.8000	58.6000	78.8854	34,340.7
Maximum	4.2259	93.1000	95.4000	90.0000	99.7993	121,292
Minimum	2.3100	35.3000	53.0000	23.3000	40.0100	15,661.2
Std. Dev.	0.4196	14.6482	8.8291	15.1268	11.8272	17,897.0
Skewness	−0.2611	−0.07699	0.0162	−0.1087	−0.4808	2.2020
Kurtosis	2.2772	2.00259	2.5436	2.2956	2.7996	9.1123
Jarque–Bera	7.7184	9.88822	2.0323	5.2770	9.7676	551.004
Probability	0.0211	0.00712	0.3620	0.0715	0.0076	0.00000

Data source: UNCTAD-Eora database and World Bank. Calculation: EViews 13. Sample: 2011–2019.

This study examines the impact of the use of ICT on economic performance, focusing on the relationship with the Logistics Performance Index (LPI). The central hypothesis is that increasing digitalization in supply chains increases logistics efficiency, which contributes to higher GDP per capita, greater trade openness and better sustainability outcomes. However, a key challenge in this analysis is the potential endogeneity problem arising from reverse causality, omitted variable bias and measurement error. To address this problem, the study applies the Arellano–Bond Generalized Method of Moments (GMM) estimator, a robust econometric approach suitable for dynamic panel data.

Simultaneity is a problem because the efficiency of logistics is both influenced by and dependent on ICT. Companies streamlining their supply chains often invest their savings in advanced digital tools, while the expansion of global trade increases the need for ICT for cross-border coordination. In addition, competitive pressures and evolving regulations are driving a cycle in which automation, real-time tracking and blockchain are increasingly utilized. To counteract this bias, lagged values of ICT adoption are used as instrumental variables to ensure that short-term fluctuations do not distort the estimated effect of ICT on logistics.

The Arellano–Bond Generalized Method of Moments (GMM) estimator is particularly useful for the analysis of dynamic panel data, especially when dealing with endogeneity issues that may not be fully accounted for in fixed-effects (FE) and random-effects (RE) models. Dynamic panel models often include lagged dependent variables as regressors, which can lead to biased estimates in traditional FE models because the lagged dependent variable is correlated with the error term. The Arellano–Bond GMM estimator solves this problem by using past values of the dependent variable as instruments, thus ensuring more reliable parameter estimates. Another advantage of this estimator is its ability to account for autocorrelation in panel data. By transforming the model, e.g., by first differencing and selecting appropriate instruments, biases due to autocorrelated errors are reduced and more robust results are obtained than with FE and RE models. While FE models remove time-invariant individual effects by demeaning, they cannot fully correct for cases where these effects are correlated with lagged dependent variables. The Arellano–Bond GMM estimator improves this by applying internal instruments, which further strengthens the validity of the estimates. In addition, this method is particularly well suited for datasets with a large number of cross-sectional units (N) but a relatively small number of time periods (T), where FE and RE models often have problems. Research also suggests that, under ideal conditions, the Arellano–Bond estimator has lower finite sample bias compared to alternative methods, making it a reliable choice for empirical analyses. To summarize, the Arellano–Bond GMM estimator offers distinct advantages over traditional FE and RE models in dynamic panel data contexts as it effectively handles endogeneity, autocorrelation, and unobserved individual effects, ultimately leading to more consistent and efficient estimates.

To further reduce bias from omitted variables, the model includes GDP per capita, trade openness and institutional quality as control variables. In addition, potential measurement errors in ICT indicators, such as broadband penetration and digital skills levels, are mitigated by using multiple ICT proxies, allowing for a more comprehensive assessment of digital infrastructure and skills. The dynamic nature of logistics performance is considered by including lagged dependent variables, which strengthens the causal identification strategy.

To check the robustness of the results, a series of diagnostic tests are performed, as outlined below:

1. Hansen J test for overidentification to ensure that the instrumental variables are exogenous and uncorrelated with the error term [37,38].
2. Arellano–Bond tests for serial correlation to check the validity of the moment conditions in the GMM estimator [39,40].
3. Variance Inflation Factor (VIF) tests to check for multicollinearity between the independent variables [41].
4. Breusch–Pagan–Lagrange multiplier (LM) test, which identifies possible cross-sectional dependence [42].
5. Pesaran's Cross-Section Dependence (CD) test, which assesses the degree of interdependence between the EU member states [43,44].
6. Pesaran's Panel Unit Root Test, which confirms the stationarity of panel data [45].

Additional robustness checks include bootstrapping to estimate standard errors, sensitivity analyses performed with EViews 13. These methodological refinements ensure that the results reflect a robust causal relationship between ICT adoption and logistics performance in the EU, rather than spurious correlations or statistical artefacts.

Table 4 summarizes the results of the panel unit root tests applied to the main variables to assess their stationarity. The tests include Levin, Lin & Chu (LLC), Breitung, Im, Pesaran and Shin (IPS), ADF-Fisher and PP-Fisher.

Table 4. Panel unit root tests' summary of probabilities.

	LPI	ICTINFR	ICTACC	ICTUSE	INTERNET	GDPPCPPP
Null: Unit root (assumes common unit root process)						
Levin, Lin & Chu t-stat	0.8370	0.0026	0.0025	0.0000	0.0000	0.0000
Breitung t-stat	0.9583	1.0000	0.3988	0.5394	0.4922	1.0000
Null: Unit root (assumes individual unit root process)						
Im, Pesaran and Shin W-stat	0.9152	0.8355	0.9250	0.4278	0.5834	0.9372
ADF-Fisher Chi-square	0.9850	0.9169	0.9997	0.0862	0.3970	0.9932
PP-Fisher Chi-square	0.0000	0.0000	0.1644	0.0000	0.0000	0.0071

Data source: UNCTAD-Eora database and World Bank. Calculation: EViews 13. Sample: 2011–2019.

For the Logistics Performance Index (LPI), most tests, including LLC (p = 0.8370), Breitung (p = 0.9583) and IPS (p = 0.9152), fail to reject the null hypothesis of a unit root, indicating non-stationarity, although the PP-Fisher test (p = 0.0000) indicates stationarity. ICT infrastructure (ICTINFR) and ICT access (ICTACC) show mixed results, with LLC (p = 0.0026 and p = 0.0025) and PP-Fisher (p = 0.0000 and p = 0.1644) supporting stationarity, while other tests do not. ICT use (ICTUSE) and Internet use in % of all households (INTERNET) consistently show signs of stationarity in the LLC and PP-Fisher tests (p = 0.0000 for both), indicating greater reliability. For GDP per capita (GDPPCPPP), stationarity is supported by LLC (p = 0.0000) and PP-Fisher (p = 0.0071), while other tests, such as Breitung (p = 1.0000) and ADF-Fisher (p = 0.9932), indicate non-stationarity. While some variables show consistent signs of stationarity, others, particularly LPI and GDPPCPPP,

yield mixed results, indicating that non-stationary variables may need to be transformed or differenced to ensure robust regression analysis. Thus, in continuation, all variables shall be first differenced to ensure stationarity.

We test the following equation with the Arellano–Bond GMM FD:

$$GDPPCPPP_{i,t} = \beta_1 \cdot GDPPCPPP_{i,t-1} + \beta_2 \cdot LPI_{i,t} + \beta_3 \cdot ICTINFR_{i,t} + \beta_4 \cdot ICTACC_{i,t} + \beta_5 \cdot ICTUSE_{i,t} + \epsilon_t \quad (1)$$

4. Results and Discussion

Table 5 shows the results of the Arellano–Bond GMM FD panel estimation, which highlight the significant positive impact of ICT adoption and logistics performance on GDP per capita (GDPPCPPP). The lagged dependent variable, GDPPCPPP (−1), has a coefficient of 0.7039, indicating strong persistence in economic performance. Among the ICT variables, ICT utilization (ICTUSE) has the strongest effect with a coefficient of 123.0586, followed by ICT access (ICTACC) with 102.2585 and ICT infrastructure (ICTINFR) with 55.3521, all statistically significant (p = 0.0000). The Logistics Performance Index (LPI) has the greatest influence with a coefficient of 894.6671 and thus underlines the importance of logistics efficiency for economic growth. The robustness of the model is confirmed by the J-statistic (23.81055, p = 0.3023), which confirms the validity of the instruments and the absence of overidentification problems.

Table 5. Panel data on generalized method of moments dependent variable: GDPPCPPP.

Variable	Coefficient	Std. Error	t-Statistic	Prob.
GDPPCPPP (−1)	0.7039	0.0118	59.5199	0.0000
LPI	894.6671	80.0387	11.1779	0.0000
ICTINFR	55.3521	9.4565	5.8534	0.0000
ICTACC	102.2585	11.9617	8.5488	0.0000
ICTUSE	123.0586	11.6441	10.5683	0.0000
Mean dependent var	1868.843	S.D. dependent var		1628.326
S.E. of regression	1882.954	Sum squared resid		6.28 × 108
J-statistic	23.8106	Instrument rank		26
Prob (J-statistic)	0.3023			

Sample: 2013–2019. Total panel (balanced) observations: 182. White period instrument weighting matrix. Cross-section fixed (first differences). Instrument specification: @DYN (GDPPCPPP, −2); 27 EU Member States.

Using the countries in the sample as instruments in the Arellano–Bond GMM FD panel estimation is generally appropriate when certain conditions are met. Lagged dependent variables, such as GDPPCPPP (−1), and country-specific variables can serve as valid instruments if they are uncorrelated with the error term and thus fulfil the orthogonality condition. This is an established approach in dynamic panel models, where lagged levels or differences of variables help to account for endogeneity and ensure consistent coefficient estimation, especially in the Arellano–Bond framework. The first-difference transformation removes time-invariant country-specific effects, reduces bias due to omitted variables and supports the exogeneity of the instruments. In this analysis, the number of instruments (25) corresponds to the number of cross-sections, so that the sufficiency condition of the instruments is met. Despite these advantages, potential problems must be considered. Overidentification, which occurs when too many instruments are used, can lead to overfitting of the endogenous variables and undermine the validity of the GMM estimator. This problem is addressed with the J-statistic (Hansen test for overidentifying restrictions). In this study, the p-value of 0.3023 for the J-statistic confirms the validity of the instruments and indicates that they are not overidentified. Cross-sectional dependence is another potential problem, as economic shocks in one country may affect other

countries, which could violate the exogeneity assumption of the instruments. To test for cross-sectional dependence, Pesaran's CD test can be applied. If cross-sectional dependence is present, alternative estimators, such as Common Correlated Effects (CCEs), may be more appropriate. The strength of the instrument is also crucial, as weak instruments that are poorly correlated with endogenous variables can lead to biased estimates and unreliable results. Therefore, it is important to confirm the strength of the instruments during the analysis.

Table 6 shows the results of the Arellano–Bond test for serial correlation.

Table 6. Arellano–Bond serial correlation test.

Test Order	m-Statistic	rho	SE (rho)	Prob.
AR (1)	−1.481888	−219,053,458.743	147,820,566.977	0.1384
AR (2)	−0.345733	−10,731,952.738	31,041,145.140	0.7295

Sample: 2011–2019. Included observations: 182.

The AR (1) statistic is marginally significant (p = 0.1384), but the AR (2) statistic is not (p = 0.7295), indicating that there is no second-order serial correlation and confirming the moment conditions of the model. These results emphasize that ICT usage and logistic performance are important drivers of economic outcomes, with ICT usage exerting the strongest influence, while the validity of the instruments and the absence of serial correlation confirm the reliability of the GMM estimates.

Tables 5 and 6 indicate that ICT use and logistics performance are statistically associated with higher economic development in the European Union. The positive association between ICT usage (ICTUSE) and GDP per capita suggests that effective digital technology integration is linked with enhanced productivity, innovation, and overall economic efficiency. This finding supports policy initiatives that encourage digital transformation—especially in sectors where ICT can streamline processes, improve connectivity, and add value. The associations observed for ICT access (ICTACC) and ICT infrastructure (ICTINFR) further underscore the importance of broad availability and robust infrastructure for effective ICT adoption. Similarly, the influence of the Logistics Performance Index (LPI) suggests that efficient, sustainable logistics systems are correlated with economic growth. This aligns with the study's focus on ICT's role in enhancing logistics performance through improved supply chain efficiency, cost reduction, and increased trade competitiveness. Overall, these results indicate that ICT-related improvements in logistics are associated with benefits for individual EU Member States and contribute to regional integration and economic cohesion within the bloc. The robustness of these results is confirmed by the statistical reliability of the model, which is confirmed by the J-statistic and the absence of second-order serial correlation. This ensures that the observed correlations are not artefacts of methodological problems, but reflect real dynamics in the data. These results make it clear that targeted investment in ICT infrastructure and digital literacy, as well as policy measures to improve logistics systems, are needed to fully exploit the economic benefits of technology and strengthen competitiveness in the global economy.

This is the explicit Arellano–Bond GMM FD model:

$$GDPPCPPP_{i,t} = 0.7 \cdot GDPPCPPP_{i,t-1} + 895 \cdot LPI_{i,t} + 55 \cdot ICTINFR_{i,t} + 102 \cdot ICTACC_{i,t} + 123 \cdot ICTUSE_{i,t} + \epsilon_t \quad (2)$$

At the end, a comparative analysis was conducted to check the robustness of the results by using fixed and random effects models, a subsample analysis by degree of digitization and alternative ICT indicators. FE and RE models were not statistically significant, confirming that the Arellano–Bond GMM was the most appropriate approach. The analysis

of the subsample showed that ICT access has a stronger influence in digitally advanced economies, while alternative ICT indicators provided consistent results.

To assess the robustness of our results, we re-estimate the model by logarithmically transforming GDP per capita (PPP) as the dependent variable. This transformation accounts for possible biases in the GDP data and allows for an elasticity-based interpretation of the coefficients. The results are shown in Table 7.

Table 7. Panel data on generalized method of moments dependent variable: LOG (GDPPCPPP).

Variable	Coefficient	Std. Error	t-Statistic	Prob.
LOG (GDPPCPPP (−1))	0.6967	0.0160	43.6156	0.0000
LPI	0.0262	0.0024	10.9667	0.0000
ICTINFR	0.0013	0.0002	6.4222	0.0000
ICTACC	0.0017	0.0003	5.2480	0.0000
ICTUSE	0.0028	0.0003	9.3352	0.0000
Mean dependent var	0.0476	S.D. dependent var		0.0296
S.E. of regression	0.0367	Sum squared resid		0.2378
J-statistic	24.9389	Instrument rank		26
Prob (J-statistic)	0.2498			

Sample: 2013–2019. Total panel (balanced) observations: 182. White period instrument weighting matrix. Cross-section fixed (first differences). Instrument specification: @DYN (GDPPCPPP, −2); 27 EU Member States.

The results are consistent with the main findings from our first regression. The coefficient for LPI (0.026) remains positive and highly significant ($p < 0.001$), confirming that improvements in logistics performance contribute to economic growth. The ICT-related variables—ICT infrastructure, ICT access and ICT usage—also show significant positive effects on GDP per capita, supporting the argument that digitalization improves economic performance. The persistence of GDP is also evident as the lagged dependent variable (LOG (GDPPCPPP (−1)) has a coefficient of 0.696, indicating a strong dynamic relationship. These results suggest that ICT adoption and logistics performance are statistically positively associated with economic development in the EU and that our conclusions are robust to the choice of GDP specification. The AR (1) Prob. Value of 0.096 indicates the lack of first-order serial correlation once again. However, the presence of a second-order serial correlation (AR (2)) detected in the Arellano–Bond test raises concerns about the validity of the instruments. To address this issue, we re-estimated the model using the orthogonal deviance transformation, which eliminates individual fixed effects while preserving more information in the panel (Table 8).

Table 8. Panel data on generalized method of moments dependent variable: LOG (GDPPCPPP).

Variable	Coefficient	Std. Error	t-Statistic	Prob.
LOG (GDPPCPPP (−1))	0.7734	0.0146	52.9726	0.0000
LPI	0.0202	0.0036	5.6795	0.0000
ICTINFR	0.0007	0.0002	3.4810	0.0019
ICTACC	0.0019	0.0003	6.6088	0.0000
ICTUSE	0.0012	0.0004	3.2830	0.0030
Mean dependent var	−0.1116	S.D. dependent var		0.0634
S.E. of regression	0.0261	Sum squared resid		0.1200
J-statistic	25.1376	Instrument rank		26
Prob (J-statistic)	0.1962			

Transformation: orthogonal deviations. Sample (adjusted): 2013–2019. Periods included: 7. Cross-sections included: 26. Total panel (balanced) observations: 182. White period (period correlation) instrument weighting matrix. White period (cross-section cluster) standard errors and covariance.

The results of the orthogonal deviance GMM confirmed the significance and direction of the key variables while solving the AR (2) problem, suggesting that this is the more reliable specification in this context.

The key relationships between ICT, logistics performance and economic growth remain strong and statistically significant across different model specifications. The robustness check with log-transformed GDP confirms the validity of our main results and shows that ICT adoption and logistics efficiency are important drivers of economic development in the EU.

5. Conclusions

This study highlights the transformative role of ICT in improving the efficiency, sustainability and resilience of supply chains in the European Union. Digital tools such as AI, blockchain, IoT and big data analytics have significantly improved logistics performance, promoted economic integration, optimized resource allocation and supported environmental sustainability. By using ICT, companies and policy makers can improve supply chain transparency, reduce inefficiencies and create more responsive and adaptable logistics networks. However, the differences in ICT use across EU Member States highlight the need for targeted policy action and investment to bridge the digital divide. Ensuring equal access to advanced digital infrastructure is critical to maximizing ICT-related benefits across the region.

To bridge the digital divide between EU Member States and maximize the economic benefits of ICT use, this study proposes targeted policy measures aimed at developing digital infrastructure, improving skills and harmonizing the regulatory framework. The expansion of broadband infrastructure, especially in underserved regions, is crucial to ensure equal access to ICT-enabled logistics solutions that enable real-time tracking, e-commerce integration and data-driven supply chain optimization. At the same time, comprehensive digital literacy and vocational training initiatives should be prioritized to close the ICT skills gap, especially in Central and Eastern European countries, to enable companies to fully leverage AI-enabled logistics, blockchain-based traceability and IoT-enabled inventory management. Strengthening public–private partnerships (PPPs) is critical to accelerating the adoption of advanced digital technologies, as collaboration between governments, industry leaders and research institutions can incentivize private sector investment and drive innovation in digital logistics. In addition, harmonizing regulatory frameworks across the EU will facilitate seamless digital trade, reduce inefficiencies and improve supply chain interoperability by establishing common standards for cybersecurity, data protection, digital taxation and cross-border transactions. By implementing these targeted strategies, the EU can promote a more resilient, efficient and inclusive digital economy and ensure that the adoption of ICT translates into tangible improvements in logistical performance, economic inclusion and long-term sustainability in an increasingly competitive global market.

This study has potential limitations from a methodological point of view arising from the limited amount and variety of available data, while empirical limitations are related to the reliability of the data. In addition, reproducibility may be limited by the large amount of data, which makes manual verification of large datasets error prone.

As digitalization will continue to reshape global trade and logistics, closing the gaps in digital literacy, cybersecurity and regulatory frameworks is critical to fostering a more inclusive and sustainable digital economy. Future research should further explore the long-term impact of ICT on global supply chains, particularly in the context of economic resilience and environmental impact.

The Internet of Things (IoT) is revolutionizing supply chain management by enabling real-time tracking of goods, vehicles and environmental conditions. IoT sensors, RFID tags and GPS devices provide continuous streams of data that improve inventory tracking, warehouse efficiency and delivery optimization. By integrating IoT into logistics, companies can reduce inventory errors, improve route planning and increase supply chain visibility. Thanks to real-time data collection, companies can anticipate disruptions, minimize delays and optimize resource allocation, resulting in cost savings and greater resilience. The findings of this study are consistent with these benefits and show that the use of ICT, including the Internet of Things, significantly improves logistics performance, efficiency and economic integration in EU supply chains. In addition, new technologies such as AI-driven automation, blockchain-assisted traceability and smart logistics solutions as well as advanced IoT applications in supply chains—especially in terms of quality of service, load balancing and software-defined networks—need to be further explored to assess their potential for sustainable supply chain transformation. These modern ICT developments are in line with the evolving perspectives of digitalization-driven logistics performance and supply chain transformation and offer significant potential to improve effectiveness, efficiency, climate resilience and economic integration within European supply chains.

By driving the digitalization of supply chains, the EU can strengthen its economic competitiveness while contributing to a more sustainable and connected global trade ecosystem.

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Abbreviations

The following abbreviations are used in this manuscript:

GMM FD	Generalized Method of Moments First Differences
GDPPCPPP	Gross Domestic Product Per Capita Purchasing Power Parity
LPI	Logistics Performance Index
ICT	Information and Communication Technology
ICTINFR	Information and Communication Technology Infrastructure
ICTACC	Information and Communication Technology Access
ICTUSE	Information and Communication Technology Use

Appendix A

For testing coefficient stability against small changes in variables, we show two more GMM FD models. The first (Tables A1 and A2) includes the additional variable INTERNETUSE, which represents the percentage of households with active internet usage. The second (Tables A3 and A4) model does not include the ICTUSE variable but includes the GDPPCPPP (−2) variable that shows the autoregressive component of the second order of the dependent variable.

Table A1. Panel data on generalized method of moments dependent variable: GDPPCPPP.

Variable	Coefficient	Std. Error	t-Statistic	Prob.
GDPPCPPP (−1)	0.6834	0.0130	52.5556	0.0000
LPI	864.1030	193.4368	4.4671	0.0001
ICTINFR	37.8462	9.7052	3.8996	0.0006
ICTACC	116.2639	13.2911	8.7475	0.0000
ICTUSE	65.0223	17.1735	3.7862	0.0009
INTERNETUSE	196.5449	36.2073	5.4283	0.0000
Mean dependent var	1868.843	S.D. dependent var		1628.33
S.E. of regression	1840.227	Sum squared resid		5.96×10^8
J-statistic	24.3337	Instrument rank		26
Prob (J-statistic)	0.2281			

Sample total observations: 182. Instrument specification: @DYN (GDPPCPPP, −2).

Table A2. Arellano–Bond Serial Correlation Test.

Test Order	m-Statistic	rho	SE (rho)	Prob.
AR (1)	−1.1961	−218,770,689.1311	182,909,828.2865	0.2317
AR (2)	0.9671	35,147,657.4188	36,344,707.9228	0.3335

Table A3. Panel data on generalized method of moments dependent variable: GDPPCPPP.

Variable	Coefficient	Std. Error	t-Statistic	Prob.
GDPPCPPP (−1)	0.4852	0.0130	37.2903	0.0000
GDPPCPPP (−2)	0.2092	0.0128	16.3857	0.0000
LPI	1036.04	349.159	2.9672	0.0065
ICTINFR	87.2864	8.8884	9.8203	0.0000
ICTACC	100.400	8.1093	12.3808	0.0000
INTERNETUSE	226.525	25.3954	8.9199	0.0000
Mean dependent var	1976.08	S.D. dependent var		1695.28
S.E. of regression	1810.99	Sum squared resid		4.92×10^8
J-statistic	22.5838	Instrument rank		26
Prob (J-statistic)	0.3097			

Sample: 2014–2019. Cross-sections included: 26. Total observations: 156.

Table A4. Arellano–Bond Serial Correlation Test.

Test Order	m-Statistic	rho	SE (rho)	Prob.
AR (1)	−1.4251	−145,116,950.8803	101,828,170.0827	0.1541
AR (2)	0.1356	5,526,767.2645	40,753,375.3675	0.8921

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