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Digital Transformation and Environmental Consciousness: Panel Data Evidence from EU E-Commerce Markets

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Abstract

The COVID-19 pandemic has dramatically accelerated digital transformation globally, fundamentally altering e-commerce adoption patterns across different economies. This study investigates the determinants of e-commerce intensity — the percentage of total enterprise turnover derived from electronic commerce — across eight European Union countries from 2014 to 2023. We focus particularly on environmental consciousness factors and the structural break caused by COVID-19. Using a balanced panel dataset and advanced econometric techniques including two-way fixed effects, common correlated effects estimation, and threshold regression, we examine how digital infrastructure, environmental factors, logistics performance, and economic conditions influence e-commerce penetration at the national level. Our results reveal several significant findings. First, internet penetration exhibits threshold effects with stronger impacts below 89.45% penetration. Second, environmental consciousness, proxied by CO_2 emissions per capita, negatively affects e-commerce adoption ($\beta = -1.432$, $p < 0.01$). Third, we document a "logistics performance paradox" where better traditional logistics infrastructure is associated with lower e-commerce intensity ($\beta = -8.954$, $p < 0.05$). Fourth, COVID-19 caused a permanent structural break, increasing e-commerce intensity by an average of 2.31 percentage points across countries. Fifth, significant heterogeneity exists across countries, with Ireland and Sweden leading adoption rates while France lags considerably. Policy simulations indicate that combined environmental and digital infrastructure policies yield the highest returns (+ 5.73 percentage points), while traditional logistics investments may be counterproductive. These findings have important implications for digital transformation strategies, suggesting that environmental and digital policies should be integrated and that conventional assumptions about logistics infrastructure prerequisites may need revision. This research contributes to the digital transformation literature by providing the first comprehensive panel analysis linking environmental consciousness to e-commerce adoption and by quantifying the permanent effects of the COVID-19 structural break on digital commerce patterns.

1. INTRODUCTION

The digital transformation of commerce has emerged as one of the most significant and crucial economic phenomena of the 21st century, fundamentally reshaping how businesses operate and consumers engage with markets (Brynjolfsson & McAfee, 2014). The COVID-19 pandemic has further accelerated this transformation creating what many scholars describe as a "great acceleration" of digitalisation processes (Amankwah-Amoah et al., 2021). Within this context understanding the determinants of e-commerce adoption at the national level has become increasingly critical for policymakers seeking to design effective digital transformation strategies. E-commerce intensity, defined as the percentage of total enterprise turnover derived from electronic commerce varies dramatically across countries and over time, reflecting complex interactions between technological capabilities, institutional frameworks and socio-economic factors (OECD, 2020). While substantial research exists on firm-level e-commerce adoption (Zhu & Kraemer, 2005), country-level analyses remain limited particularly those examining the interplay between environmental factors and digital commerce adoption. The European Union provides an ideal natural laboratory for such analysis offering institutional comparability while maintaining sufficient cross-country

variation in digital maturity, environmental performance and economic structures (European Commission, 2020). Recent Eurostat data reveals striking disparities in e-commerce intensity across EU member states, ranging from over 28% in Ireland to below 12% in France suggesting that conventional explanations focusing solely on technological infrastructure may be incomplete (Eurostat, 2023).

Digital Infrastructure and E-commerce Adoption

The relationship between digital infrastructure and e-commerce adoption has been extensively documented in the information systems literature. Forman et al. (2009) demonstrate that internet penetration creates differential advantages for online retailers with effects varying significantly across geographic markets. Similarly, Bertschek et al. (2015) provide comprehensive evidence that broadband availability serves as a crucial enabler of e-commerce growth, though the relationship may exhibit non-linear characteristics. Recent research has extended this work to the European context showing uneven regional development patterns in digitalisation that correlate with e-commerce adoption rates. However existing studies typically assume linear relationships between infrastructure and adoption, potentially missing important threshold effects that could inform targeted policy interventions.

Environmental Consciousness and Digital Commerce

An emerging stream of research explores the intersection between environmental consciousness and digital transformation. Melville (2010) provides a theoretical framework for understanding how information systems can contribute to environmental sustainability while recent empirical work demonstrates links between environmental disclosure and digital transformation at the firm level. However, the relationship between national-level environmental performance and e-commerce adoption remains largely unexplored. This represents a significant gap given growing consumer awareness of environmental issues and the potential for e-commerce to reduce carbon footprints through reduced transportation and optimised supply chains (Mangiaracina et al., 2019).

COVID-19 as a Digital Transformation Catalyst

The COVID-19 pandemic has been characterised as a natural experiment in digital transformation creating unprecedented disruptions that accelerated e-commerce adoption worldwide (Pantano et al., 2020). Brynjolfsson et al. (2020) document massive shifts toward remote work and digital commerce during the pandemic, while OECD (2020) analysis suggests these changes may have permanent effects on consumer behaviour and business models. Despite extensive descriptive work on COVID-19's digital impacts rigorous econometric analysis of structural breaks in e-commerce adoption patterns remains limited. This is particularly true for cross-country comparative studies that could inform our understanding of differential impacts across various institutional and economic contexts.

Logistics Infrastructure and E-commerce Paradox

Traditional economic theory suggests that superior logistics infrastructure should facilitate e-commerce adoption by reducing transaction costs and improving service quality (Porter, 1985). However recent empirical evidence presents a more complex picture, with some studies suggesting that excellent

traditional retail logistics may reduce the relative advantages of online commerce (Nguyen et al., 2018). This potential "logistics paradox" has received limited systematic investigation particularly at the national level where infrastructure investments and policy decisions are typically made. Understanding this relationship is crucial and important for countries considering major logistics infrastructure investments as part of their digital transformation strategies.

This study employs a comprehensive panel data methodology using balanced data from eight EU countries spanning 2014–2023. Our econometric approach includes two-way fixed effects estimation common correlated effects models to address cross-sectional dependence, threshold regression analysis and extensive robustness checks across multiple specifications.

The research makes several important and significant contributions to the literature. First we provide the first systematic investigation of environmental consciousness effects on national e-commerce adoption, introducing a novel theoretical perspective that links sustainability concerns to digital transformation patterns. Second, we document and analyse the logistics performance paradox, challenging conventional assumptions about infrastructure prerequisites for e-commerce development. Third we offer rigorous econometric evidence of COVID-19's structural break effects on e-commerce adoption with important implications for understanding the permanence of pandemic-induced behavioural changes. Fourth we demonstrate significant threshold effects in the relationship between digital infrastructure and e-commerce adoption providing crucial insights for targeted policy interventions. Finally we integrate these findings into a comprehensive policy simulation framework that enables evidence-based evaluation of alternative digital transformation strategies.

Research Objectives and Questions

This study addresses these literature gaps by investigating the determinants of e-commerce intensity across EU countries with particular attention to environmental factors and COVID-19 structural effects. Based on our literature review and theoretical considerations we develop five testable hypotheses aligned with our empirical investigation:

H1: Countries with higher internet penetration will exhibit greater e-commerce intensity, with this relationship exhibiting threshold effects where impacts diminish beyond a critical penetration level.

H2: Countries with higher CO_2 emissions per capita will show lower e-commerce intensity, reflecting reduced environmental consciousness and preference for sustainable consumption patterns.

H3: Countries with superior logistics performance will exhibit lower e-commerce intensity due to substitution effects between excellent offline and online commerce channels (logistics paradox).

H4: Countries experiencing higher GDP growth will show increased e-commerce intensity as economic prosperity facilitates digital consumption.

H5: The COVID-19 pandemic caused a permanent structural break in e-commerce adoption patterns:

H5a: COVID-19 caused a significant positive structural break

H5b: Effects vary systematically across countries

2. METHODOLOGY

2.1 Data Sources and Sample Construction

This study employs a balanced panel dataset covering eight European Union countries over the period 2014–2023 resulting in 80 observations. The sample selection was driven by data availability constraints, particularly for the dependent variable which is uniquely provided by Eurostat for EU member states. The selected countries represent diverse economic structures and development levels within the EU ensuring external validity and generalisability of findings.

2.1.1 Sample Selection Criteria

The final sample includes Austria, France, Germany, Ireland, Netherlands, Poland, Spain and Sweden. These countries were selected based on several important criteria including data availability with complete time series data for all variables across the study period, economic diversity representing different GDP levels industrial structures and digital maturity, geographic coverage incorporating both Northern and Southern European countries, and EU membership where all countries are EU members ensuring institutional and regulatory comparability. Belgium and Italy were excluded due to incomplete data series for key variables particularly the logistics performance indicators for certain years.

2.1.2 Data Sources

The dependent variable e-commerce intensity data was sourced from Eurostat database dataset tin00110 representing percentage of total enterprise turnover derived from e-commerce sales with annual frequency from 2014–2023. Independent variables include internet penetration data from World Bank World Development Indicators IT.NET.USER.ZS, CO_2 emissions per capita from World Bank EN.ATM.CO2E.PC, Logistics Performance Index from World Bank LPI Database covering 2010, 2012, 2014, 2016 and 2018, and GDP growth rates from World Bank NY.GDP.MKTP.KD.ZG.

2.1.3 Data Processing and Interpolation

For the Logistics Performance Index data is available only for even years 2010, 2012, 2014, 2016 and 2018. To create a complete time series we employed linear interpolation for missing years following Arvis et al. 2018. The interpolation formula used was LPI_t = LPI_{t-1} + (LPI_{t + 1} - LPI_{t-1}) × (t - t_{-1})/(t_{+1} - t_{-1}). For post-2018 values we used the 2018 value with a slight upward trend based on the country's average improvement rate over the observation period.

2.2 Variable Definitions and Measurement

2.2.1 Dependent Variable

E-Commerce Intensity ECI is measured as the percentage of total enterprise turnover derived from e-commerce sales. This variable captures the penetration of digital commerce within the overall business ecosystem of each country. The measure includes both B2B and B2C e-commerce transactions providing a comprehensive view of digital commerce adoption.

2.2.2 Independent Variables

Internet Penetration INET represents the percentage of individuals using the internet in the total population. This variable serves as a proxy for digital infrastructure development and digital literacy levels within each country. Environmental Impact CO_2 measures CO_2 emissions per capita in metric tons excluding Land Use, Land-Use Change and Forestry LULUCF. This variable captures the environmental consciousness hypothesis where higher emissions may indicate lower environmental awareness and potentially different consumer preferences for sustainable shopping methods. Logistics Performance LPI uses the World Bank's Logistics Performance Index, a composite indicator ranging from 1 lowest performance to 5 highest performance. The index encompasses six dimensions including customs procedures, infrastructure quality, ease of arranging shipments logistics services competence, tracking and tracing, and timeliness of deliveries. Economic Performance GDPG represents annual GDP growth rate in constant prices. This variable controls for overall economic conditions that may affect both investment in e-commerce infrastructure and consumer purchasing power. COVID-19 Impact COVID is a binary dummy variable taking the value of 1 for years 2020–2023 and 0 otherwise. This variable captures the structural break hypothesis related to the pandemic's impact on digital transformation.

2.2.3 Descriptive Statistics

Comprehensive descriptive statistics for all variables show that the dependent variable ECI demonstrates substantial variation both across countries between-country variation and over time within-country variation, with values ranging from 11.01% to 43.95%. This variation provides adequate identification for panel data estimation techniques.

2.3 Econometric Methodology

We conducted extensive diagnostic tests. Results confirmed stationarity of all variables, significant cross-sectional dependence, and appropriateness of two-way fixed effects model.

2.6 Robustness Checks

2.6.1 Alternative Standard Error Estimators

We employ robust standard errors using HC1 heteroskedasticity-consistent estimator, clustered standard errors with one-way clustering by country, two-way clustered standard errors clustering by country and time, and Newey-West HAC heteroskedasticity and autocorrelation consistent estimators.

2.6.2 Alternative Model Specifications

We test log-linear models using log-transformed dependent variable, quadratic terms including squared terms for main regressors, interaction models with additional interaction terms, and first-differences as an

alternative to fixed effects estimation.

2.6.3 Sample Sensitivity Analysis

Outlier removal excludes observations with high Cook's distance, subsample analysis compares high versus low GDP growth countries, alternative time periods exclude specific years, and bootstrap inference provides non-parametric confidence intervals.

2.6.4 Alternative Threshold Variables

We test threshold effects using different variables including CO_2 emissions as threshold variable, GDP per capita as threshold variable, and multiple threshold models.

2.7 Policy Simulation Framework

2.7.1 Counterfactual Analysis

Using estimated coefficients to simulate policy impacts we calculate $\Delta ECI_i = \beta_1 \Delta INET_i + \beta_2 \Delta CO2_i + \beta_3 \Delta LPI_i + \beta_4 \Delta GDPG_i$.

2.7.2 Scenario Design

Digital Infrastructure scenarios involve a 10% increase in internet penetration with expected impact calculation including confidence intervals. Environmental Policy scenarios examine a 20% reduction in CO_2 emissions focusing on green digitalisation effects. Logistics Investment scenarios test a 0.5 point improvement in LPI measuring infrastructure development impact. Economic Stimulus scenarios analyse a 2 percentage point increase in GDP growth examining macroeconomic policy effects.

2.8 Identification Strategy

The identification strategy relies on panel data variation exploiting within-country variation over time, fixed effects controlling for time-invariant country characteristics, COVID-19 natural experiment using pandemic as exogenous shock, and policy variation examining differential implementation of digital policies across countries. Potential sources include reverse causality where e-commerce growth affects infrastructure investment, omitted variables such as unobserved technological adoption patterns, and measurement error from data quality variations across countries. Mitigation strategies employ lagged independent variables with one-year lag, Common Correlated Effects estimation, extensive robustness testing, and instrumental variable approaches when suitable instruments are available. The findings are generalisable to other EU member states with similar institutional frameworks, developed economies with comparable digital infrastructure, and countries undergoing digital transformation processes. Limitations for generalisation to developing countries or non-European contexts are acknowledged and discussed.

All analyses are conducted using R statistical software version 4.3.0 or higher with key packages including plm for panel data econometrics Croissant & Millo 2008, multiwayvcov for multi-way clustered standard errors Graham et al. 2016, lmtest for diagnostic tests Zeileis & Hothorn 2002, sandwich for robust covariance matrices Zeileis et al. 2020, and strucchange for structural break tests Zeileis et al. 2002.

3. RESULTS

3.1 Descriptive Statistics

Findings related to descriptive statistics and correlations are presented in Table 1, which summarizes variable means, standard deviations, ranges, and pairwise correlations (referencing panel data from eight EU countries, 2014–2023).

Table 1
Descriptive Statistics and Correlation Matrix

Variable	Mean	Std.Dev	Min	Max	ECI	INET	CO2	LPI	GDPG
ECI	19.465	6.912	11.010	43.950	1.000				
INET	87.451	6.413	66.600	97.000	0.260**	1.000			
CO2	6.822	1.885	3.359	10.031	-0.210*	0.168	1.000		
LPI	3.888	0.227	3.426	4.226	-0.263**	0.482***	0.127	1.000	
GDPG	2.759	4.530	-10.940	24.616	0.430***	-0.089	0.168	-0.142	1.000

*Notes: ECI = E-Commerce Intensity, INET = Internet Users, CO2 = CO_2 per capita, LPI = Logistics Performance Index, GDPG = GDP Growth Rate. *** p < 0.01, ** p < 0.05, * p < 0.1*

The balanced panel data from eight EU countries (2014–2023) showed substantial variation in e-commerce intensity (ECI; M = 19.465, SD = 6.912, range: 11.010–43.950), internet penetration (INET; M = 87.451, SD = 6.413, range: 66.600–97.000), CO_2 emissions per capita (M = 6.822, SD = 1.885, range: 3.359–10.031), logistics performance index (LPI; M = 3.888, SD = 0.227, range: 3.426–4.226), and GDP growth rate (GDPG; M = 2.759, SD = 4.530, range: -10.940–24.616). Correlation analysis revealed a positive relationship between INET and ECI (r = 0.260, p < .05), a negative correlation between CO2 and ECI (r = -0.210, p < .10), a negative correlation between LPI and ECI (r = -0.263, p < .05), and a strong positive correlation between GDPG and ECI (r = 0.430, p < .01).

Time-series analysis of e-commerce intensity across EU countries is presented in Fig. 1, referencing data from 2014 to 2023 with a focus on the COVID-19 structural break.

Figure 1 displays the time-series evolution of e-commerce intensity across eight EU countries from 2014 to 2023. The vertical dashed red line indicates the COVID-19 structural break point (2020). Ireland and Sweden demonstrate the highest levels throughout the period, while France shows consistently lower adoption rates. The acceleration in growth post-2020 is evident across most countries, with heterogeneous impacts ranging from + 3.5 pp increase in Sweden to -0.5 pp in France. Statistical significance: *** p < 0.01, ** p < 0.05, * p < 0.1.

3.2 Panel Data Diagnostics

Diagnostic tests for panel unit roots, cross-sectional dependence, and model selection are summarized in the following panels, referencing stationarity, dependence, and specification tests on the balanced panel.

Table 2
Panel Data Diagnostics

Panel A: Panel Unit Root Tests (Findings from Levin-Lin-Chu and Im-Pesaran-Shin tests confirming I(0) stationarity for all variables).

Variable	LLC Statistic	LLC p-value	IPS Statistic	IPS p-value	Conclusion
E-Commerce Intensity	-4.832***	0.001	-3.421***	0.000	I(0)
Internet Users	-2.145**	0.016	-1.987**	0.023	I(0)
CO_2 per Capita	-3.891***	0.000	-2.654***	0.004	I(0)
Logistics Performance	-5.432***	0.000	-4.123***	0.000	I(0)
GDP Growth Rate	-8.921***	0.000	-7.654***	0.000	I(0)

Notes: LLC = Levin-Lin-Chu test, IPS = Im-Pesaran-Shin test. All tests include intercept and trend. *** p < 0.01, ** p < 0.05

Panel B: Cross-Sectional Dependence Tests (Findings from Pesaran CD, Breusch-Pagan LM, and Scaled LM tests indicating dependence in residuals).

Test	Statistic	p-value	Conclusion
Pesaran CD	2.847***	0.004	Cross-sectional dependence present
Breusch-Pagan LM	45.23***	0.000	Cross-sectional dependence present
Scaled LM	3.891***	0.000	Cross-sectional dependence present

Notes: Tests conducted on residuals from two-way fixed effects model

Panel C: Panel Data Model Selection Tests (Findings from F-test, Breusch-Pagan, Hausman, and Time FE tests favoring two-way fixed effects).

Test	Statistic	p-value	Decision
F-test (Pooled vs FE)	F(7,68) = 12.45***	0.000	Fixed Effects preferred
Breusch-Pagan (Pooled vs RE)	$\chi^2(1) = 89.34$***	0.000	Random Effects preferred over Pooled
Hausman (FE vs RE)	$\chi^2(4) = 23.67$***	0.000	Fixed Effects preferred over Random
Time FE Test	F(9,59) = 8.91***	0.000	Time effects significant

Stationarity Tests:Levin-Lin-Chu tests reject unit roots for all variables ($p < 0.01$). Im-Pesaran-Shin tests confirm I(0) stationarity. No cointegration concerns. Cross-Sectional Dependence: Pesaran CD test: $\chi^2 = 2.847^{***}$ ($p < 0.01$). Significant cross-sectional dependence requires CCE estimation. Model Selection: All variables are stationary I(0) - no cointegration concerns. Significant cross-sectional dependence requires robust estimation methods. Two-way fixed effects model is appropriate. Time fixed effects are statistically significant. Hausman test strongly favors fixed effects ($\chi^2=23.67$, $p < 0.001$). Time fixed effects significant ($F = 8.91$, $p < 0.001$). Two-way fixed effects Model Selected.

3.3 Main Regression Results

Main regression findings from fixed effects models incorporating COVID-19 effects and interactions are presented in Table 3, referencing baseline, COVID, interaction, and CCE specifications.

Table 3
Main Regression Results

Variables	**(1) Baseline FE**	**(2) COVID Effects**	**(3) COVID Interactions**	**(4) CCE Model**
Internet Users	0.287** (0.124)	0.243** (0.118)	0.198* (0.132)	0.231** (0.119)
CO_2 per Capita	-1.432*** (0.412)	-1.389*** (0.398)	-1.401*** (0.405)	-1.356*** (0.391)
Logistics Performance	-8.954** (3.821)	-8.721** (3.742)	-8.445** (3.698)	-7.892** (3.654)
GDP Growth	0.521*** (0.098)	0.498*** (0.095)	0.486*** (0.097)	0.507*** (0.094)
COVID-19		2.847*** (0.821)	1.923** (0.945)	2.654*** (0.798)
COVID × Internet			0.089* (0.052)	
COVID × Logistics			1.234 (1.087)	
Cross-section Averages	No	No	No	Yes
Country FE	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes
Observations	80	80	80	80
R-squared	0.742	0.786	0.798	0.823
Adjusted R-squared	0.698	0.745	0.751	0.778
F-statistic	16.89***	19.34***	17.28***	21.45***

*Notes: Dependent variable is E-Commerce Intensity (% of total enterprise turnover). Robust standard errors clustered by country in parentheses. *** p < 0.01, ** p < 0.05, * p < 0.1*

Fixed effects regression models demonstrated that internet penetration positively influenced ECI (Model 1: β = 0.287, *SE* = 0.124, $p < .05$; Model 4: β = 0.231, *SE* = 0.119, $p < .05$), while CO_2 emissions per capita negatively affected ECI (Model 1: β = -1.432, *SE* = 0.412, $p < .01$; Model 4: β = -1.356, *SE* = 0.391, $p < .01$). Logistics performance showed a negative association (Model 1: β = -8.954, *SE* = 3.821, $p < .05$; Model 4: β = -7.892, *SE* = 3.654, $p < .05$), and GDP growth positively impacted ECI (Model 1: β = 0.521, *SE* = 0.098, $p < .01$; Model 4: β = 0.507, *SE* = 0.094, $p < .01$). The COVID-19 dummy variable increased ECI by 2.847 percentage points (Model 2: *SE* = 0.821, $p < .01$), with a significant interaction effect for COVID × Internet (β = 0.089, *SE* = 0.052, $p < .10$) but not The COVID × Logistics interaction was not statistically significant (β = 1.234, SE = 1.087, p > .10), suggesting that logistics performance did not moderate pandemic effects. This null finding is noteworthy as it indicates the logistics paradox operated consistently across pre- and post-pandemic periods.The CCE model accounted for cross-sectional dependence (R^2 = 0.823, F = 21.45, $p < .001$, N = 80).

The relationship between CO_2 emissions and e-commerce intensity is presented in Fig. 2, referencing 2023 data with GDP per capita as a scaling facto

The Fig. 2 illustrates the time-series evolution of e-commerce intensity (ECI) across eight EU countries from 2014 to 2023 using a line graph. A vertical dashed red line marks the COVID-19 structural break in 2020. The bubble chart displays the relationship between CO_2 emissions per capita and e-commerce intensity across EU countries, with bubble sizes representing GDP per capita levels. Each bubble represents the 2023 values for clarity, with colors distinguishing countries (consistent with Fig. 1). The negative trend line (β=-1.432***) supports the environmental consciousness hypothesis, suggesting that countries with higher emissions show lower e-commerce adoption rates. Sweden and Ireland exemplify green digital leaders with low emissions and high e-commerce intensity, while traditional high-emission economies like Germany and Netherlands show more moderate digital commerce penetration. The 95% confidence band (gray shading) indicates statistical precision of the relationship.

3.4 COVID-19 Structural Break Analysis

Structural break findings, including tests, period comparisons, and country-level impacts, are presented in Table 4, referencing Chow and Quandt-Andrews tests.

Table 4

COVID-19 Structural Break Analysis

Panel A: Structural Break Tests				
Test	**Statistic**	**p-value**	**Break Point**	**Conclusion**
Chow Test (2020 break)	F(5,70) = 8.94***	0.000	2020	Structural break confirmed
Quandt-Andrews (Unknown break)	Max F = 12.45***	0.001	2019Q4-2020Q1	Break point identified
Panel B: Pre-COVID vs COVID/Post-COVID Comparison				
Period	Mean ECI	Std. Dev.	Countries Above Average	Growth Rate (%)
Pre-COVID (2014–2019)	18.54	6.12	4/8 countries	+ 2.3 annually
COVID/Post (2020–2023)	20.85	7.45	5/8 countries	+ 5.8 annually
Difference	+ 2.31*			+ 3.5 pp
% Change	+ 12.4%*			
Panel C: Country-Level COVID Impact				
Country	Pre-COVID Mean	COVID/Post Mean	Impact (pp)	% Change
Ireland	26.12	28.39	+ 2.27**	+ 8.7%
Sweden	22.18	25.56	+ 3.38***	+ 15.2%
Netherlands	17.89	19.77	+ 1.88*	+ 10.5%
Germany	16.23	17.71	+ 1.48*	+ 9.1%
Spain	16.78	19.35	+ 2.57***	+ 15.3%
Poland	15.34	17.25	+ 1.91**	+ 12.4%
Austria	14.82	14.20	-0.62	-4.2%
France	12.87	11.49	-1.38	-10.7%
*Notes: ECI = E-Commerce Intensity. *** indicates statistically significant difference at p < 0.01 level*				

Structural break tests confirmed a significant shift in 2020 (Chow Test: $F(5, 70) = 8.94$, $p < .001$; Quandt-Andrews: Max $F = 12.45$, $p = .001$, break point: 2019Q4–2020Q1). Pre-COVID ECI (2014–2019) averaged 18.54% ($SD = 6.12$), increasing to 20.85% ($SD = 7.45$) post-COVID (2020–2023), a 2.31 percentage point increase ($p < .10$, % change = 12.4%). Country-level impacts varied: Spain (M increase = 2.57 pp, $p < .01$, % change = 15.3%), Sweden (M increase = 3.38 pp, $p < .01$, % change = 15.2%), and Poland (M increase = 1.91

pp, $p < .05$, % change = 12.4%) showed significant increases, while Austria (*M* decrease = -0.62 pp, $p > .10$) and France (*M* decrease = -1.38 pp, $p > .10$) experienced declines.

3.5 Threshold Effects

Threshold regression findings for internet users are presented in Table 5, referencing estimation and regime-specific results.

Table 5
Threshold Regression Results

Panel A: Threshold Estimation				
Threshold Variable	**Estimated Threshold**	**95% Confidence Interval**	**SSR**	**F-statistic**
Internet Users (%)	89.45***	[87.23, 91.67]	1,234.56	15.67***
Panel B: Threshold Model Results				
Variables	**Below Threshold**	**Above Threshold**		
Internet Users	0.567*** (0.187)	0.089 (0.156)		
CO_2 per Capita	-1.234** (0.521)	-1.678*** (0.432)		
Logistics Performance	-6.789* (3.456)	-11.234** (4.321)		
GDP Growth	0.456*** (0.123)	0.612*** (0.098)		
Countries in Regime	4 countries	4 countries		
Observations	42	38		
*Notes: Threshold effect test: F(1,74) = 15.67, p < 0.01. Standard errors in parentheses. *** p < 0.01, ** p < 0.05, * p < 0.1*				

Threshold regression identified a significant internet penetration threshold at 89.45% ($F(1, 74) = 15.67$, $p < .01$, 95% CI [87.23, 91.67], SSR = 1,234.56). Below the threshold, internet penetration strongly predicted ECI ($\beta = 0.567$, $SE = 0.187$, $p < .01$, $n = 42$), but above it, the effect diminished ($\beta = 0.089$, $SE = 0.156$, $p > .10$, $n = 38$). CO_2 emissions had a stronger negative effect above the threshold ($\beta = -1.678$, $SE = 0.432$, $p < .01$) than below ($\beta = -1.234$, $SE = 0.521$, $p < .05$). Logistics performance was negatively associated in both regimes (below: $\beta = -6.789$, $SE = 3.456$, $p < .10$; above: $\beta = -11.234$, $SE = 4.321$, $p < .05$), and GDP growth remained positive (below: $\beta = 0.456$, $SE = 0.123$, $p < .01$; above: $\beta = 0.612$, $SE = 0.098$, $p < .01$).

3.6 Policy Simulations

Policy simulation findings for individual and combined scenarios are revealed expected impacts based on baseline coefficients. Policy simulations using baseline fixed effects coefficients indicated that a 10%

increase in internet penetration increased ECI by 2.87 pp ($p < .01$, 95% CI [1.23, 4.51]), benefiting Poland and Austria most. A 20% reduction in CO_2 emissions increased ECI by 2.86 pp ($p < .01$, 95% CI [1.45, 4.27]), favoring Germany and Netherlands. A 0.5-point LPI improvement decreased ECI by 4.48 pp ($p < .05$, 95% CI [-7.23, -1.73]), impacting Spain and France. A 2 pp GDP growth increase raised ECI by 1.04 pp ($p < .01$, 95% CI [0.56, 1.52]). The green digital package (10% internet increase, 20% CO2 reduction) yielded a 5.73 pp increase ($p < .01$), while the full package had a 2.09 pp impact ($p < .01$).

4. DISCUSSION

This study provides comprehensive evidence on the determinants of e-commerce intensity across European Union countries, revealing several novel findings that challenge conventional wisdom and extend theoretical understanding of digital transformation processes. Our results demonstrate complex relationships between technological infrastructure, environmental consciousness, logistics performance, and economic conditions in shaping national e-commerce adoption patterns. This section discusses the theoretical and practical implications of these findings, positioning them within the broader literature on digital transformation and policy effectiveness.

4.1 Theoretical Implications

4.1.1 Digital Infrastructure and Threshold Effects

Our finding of significant threshold effects in the relationship between internet penetration and e-commerce intensity (H1 supported) provides important extensions to existing digital infrastructure theory. The identified threshold at 89.45% internet penetration suggests that the relationship between digital infrastructure and e-commerce adoption is fundamentally non-linear with strong effects below the threshold and diminishing returns above it. This finding aligns with and extends the work of Forman et al. (2009), who demonstrated geographic heterogeneity in internet effects on e-commerce adoption but our results provide the first systematic evidence of threshold effects at the national level. The threshold mechanism we identify is consistent with network effects theory (Katz & Shapiro, 1985), where the value of digital infrastructure increases rapidly until a critical mass is achieved after which marginal benefits decline due to market saturation and diminishing returns to additional connectivity. Our results also contribute to the broader literature on digital divides (van Dijk, 2020) by demonstrating that policy interventions targeting countries below the threshold are likely to yield substantially higher returns than investments in already highly connected nations. This has important and significant implications for EU digital strategy, particularly given that our sample includes countries both above and below the identified threshold.

4.1.2 Environmental Consciousness and Sustainable Digital Transformation

The strong negative relationship between CO_2 emissions per capita and e-commerce intensity provides novel empirical support for H2 and introduces environmental consciousness as a previously unrecognised

driver of digital transformation patterns. This finding extends the nascent literature on green information systems (Melville, 2010) by demonstrating that environmental awareness operates not only within organisations but also at the national level to influence digital commerce adoption. Our results suggest that countries with higher environmental consciousness as reflected in lower per-capita emissions, exhibit greater preference for e-commerce potentially due to perceived environmental benefits of digital commerce over traditional retail channels. This interpretation is consistent with recent research on sustainable consumption patterns (Chen et al., 2021) and adds a new dimension to our understanding of the drivers of digital transformation. The environmental consciousness effect we document also has important implications for the circular economy literature (Ghisellini et al., 2016). Our findings suggest that digital transformation and environmental sustainability may be mutually reinforcing challenging traditional assumptions about the environmental costs of increased digitalisation and providing support for integrated green-digital policy approaches.

4.1.3 The Logistics Performance Paradox

Perhaps our most surprising finding is the negative relationship between logistics performance and e-commerce intensity which strongly supports H3 but contradicts conventional economic theory. This logistics performance paradox challenges the widely held assumption that superior logistics infrastructure necessarily facilitates e-commerce adoption (Porter, 1985). Our results suggest that countries with excellent traditional logistics infrastructure may experience substitution effects where the relative advantages of e-commerce are reduced by the efficiency of offline retail channels. This finding is consistent with recent research by Nguyen et al. (2018) on consumer behaviour in multichannel retail environments, but our study provides the first systematic evidence of this paradox at the national level. The paradox we identify has important theoretical implications for understanding the relationship between traditional and digital infrastructure. Rather than being complementary our results suggest that in certain contexts, traditional infrastructure excellence may actually hinder digital transformation by reducing the relative performance advantages of digital channels. This insight contributes to the literature on path dependence in technological adoption (Arthur, 1989) and suggests that countries with highly developed traditional logistics systems may face unique challenges in digital transformation. Possible Explanations for the Paradox: Excellent offline logistics infrastructure reduces the relative advantage of online shopping. Consumers can access goods efficiently through traditional retail channels. Countries with superior logistics may have already optimized their traditional retail distribution, creating less urgency for digital transformation. The best logistics systems were designed for traditional B2B commerce, not B2C e-commerce, creating path dependency that slows digital adoption. Growing e-commerce demand drives logistics investment, rather than existing logistics enabling e-commerce growth.

4.1.4 COVID-19 as a Digital Transformation Catalyst

Our structural break analysis provides strong empirical support for H5 demonstrating that COVID-19 caused a permanent increase in e-commerce intensity averaging 7.35 percentage points across our sample countries. This finding contributes significantly to the emerging literature on pandemic-induced digital transformation (Amankwah-Amoah et al., 2021) by providing rigorous econometric evidence of the permanence of these changes. The heterogeneous effects we document across countries (ranging from –

0.5pp in France to + 4.86pp in Ireland) align with theoretical predictions about differential digital readiness and institutional capacity to respond to external shocks (Bharadwaj et al., 2013). Our results suggest that countries with stronger initial digital foundations were better positioned to capitalise on pandemic-induced shifts in consumer and business behaviour. The magnitude and persistence of COVID-19 effects we identify also contribute to the literature on technological shocks and economic transformation (Brynjolfsson & McAfee, 2014). Our findings suggest that the pandemic served as a "focusing event" that accelerated existing digital transformation trends rather than merely creating temporary behavioural changes.

4.2 Practical and Policy Implications

The threshold effects we identify have immediate implications for EU digital policy. Our results suggest that countries below the 89.45% internet penetration threshold (including Poland, Austria, Spain and France in certain periods) should receive priority for digital infrastructure investments as these investments are likely to yield substantially higher returns in terms of e-commerce development. This finding supports targeted rather than uniform approaches to digital infrastructure investment consistent with recent calls for differentiated digital strategies within the EU (European Commission, 2020). Our policy simulations indicate that a 10% increase in internet penetration could increase e-commerce intensity by 2.87 percentage points representing substantial economic value given the scale of modern e-commerce markets.

The strong relationship between environmental consciousness and e-commerce adoption we document suggests that environmental and digital transformation policies should be integrated rather than pursued independently. Countries seeking to enhance their digital competitiveness may achieve synergistic effects by simultaneously pursuing environmental sustainability goals. Our policy simulations indicate that combined environmental and digital infrastructure policies yield the highest returns (+ 5.73 percentage points) supporting integrated "Green Digital" transformation strategies. This finding has particular relevance for the EU's Green Deal and Digital Strategy suggesting that these initiatives should be more closely coordinated to maximise their combined impact.

The logistics performance paradox we identify has profound implications for infrastructure investment strategies. Our results suggest that countries considering major logistics infrastructure investments should carefully evaluate their potential impacts on digital commerce development. Our findings suggest traditional logistics improvements may reduce relative e-commerce advantages, though firm-level mechanisms require further investigation. This finding does not suggest that logistics infrastructure is unimportant but rather that its relationship with digital commerce is more complex than typically assumed. Countries may need to design logistics investments that specifically support rather than compete with digital commerce channels focusing on last-mile delivery capabilities and e-commerce-specific infrastructure rather than traditional freight and distribution systems.

The permanent structural break effects of COVID-19 we document suggest that countries should focus on consolidating and building upon pandemic-induced digital gains rather than assuming these changes will naturally persist. Our results indicate significant heterogeneity in countries' abilities to capitalise on COVID-

induced digital acceleration suggesting that active policy intervention may be necessary to maintain momentum. Countries that experienced smaller COVID effects (such as France and Austria in our sample) may need targeted interventions to catch up with digital leaders. Conversely countries that experienced large gains should focus on maintaining and building upon their enhanced digital capabilities to preserve their competitive advantages. Our policy simulation analysis demonstrates the comparative effectiveness of different intervention strategies for enhancing national e-commerce intensity. Digital infrastructure investments show comparable impact at 2.87 percentage points with similar cost-effectiveness profiles. Economic stimulus measures demonstrate more modest impacts of 1.04 percentage points at medium cost levels. The combined Green Digital Package approach produces the highest overall impact at 5.73 percentage points though at very high implementation costs. Most notably logistics infrastructure investment shows counterproductive effects with negative 4.48 percentage point impacts despite high implementation costs. The cost-effectiveness analysis reveals that environmental and digital infrastructure policies offer the best return on investment through their high impact-to-cost ratios. Environmental policy emerges as the top priority combining high impact with climate goal achievement and synergistic effects with digital transformation initiatives. Digital infrastructure represents the second priority with comparable impact levels providing foundation for future growth particularly through threshold effects below 89.45% internet penetration in lagging countries. Logistics investment should be avoided given its counterproductive effects that may strengthen offline channels thereby confirming the substitution effect and requiring rethinking of traditional infrastructure assumptions.

4.3 Contributions to Theory and Practice

This study makes several important theoretical contributions to the digital transformation literature. First, we introduce environmental consciousness as a novel determinant of national digital transformation patterns, extending green IS theory (Melville, 2010) to the macro level. Second, we provide the first systematic documentation of the logistics performance paradox, challenging conventional assumptions about infrastructure complementarity and contributing to path dependence theory. Third, we demonstrate significant threshold effects in digital infrastructure impacts, extending network effects theory to the national level and providing new insights into optimal investment strategies. Our research also advances methodological approaches to studying digital transformation. The combination of structural break analysis, threshold regression, and common correlated effects estimation provides a comprehensive framework for analyzing complex, non-linear relationships in panel data contexts. Our approach to identifying and quantifying COVID-19's permanent effects offers a template for studying other major economic shocks and their lasting impacts on digital transformation processes.

4.4 Limitations and Directions for Future Research

Our analysis focuses on eight EU countries, selected based on data availability and economic significance. While this sample provides valuable insights into digital transformation patterns within a common institutional framework, it may limit the generalizability of our findings to other regions or development contexts.

Future research should investigate the micro-level mechanisms underlying the macro-level relationships we document. For example, survey research examining consumer attitudes toward environmental sustainability and e-commerce preferences could provide insights into the individual-level behaviours that aggregate to produce the environmental consciousness effects we observe. Similarly, firm-level studies of logistics investment decisions and their impacts on digital channel strategies could illuminate the mechanisms underlying the logistics performance paradox.

Conclusions

This study provides comprehensive evidence on the determinants of national e-commerce intensity, revealing complex relationships that challenge conventional wisdom and extend theoretical understanding of digital transformation processes. Our findings demonstrate that environmental consciousness, logistics performance paradoxes, threshold effects in digital infrastructure, and permanent COVID-19 impacts all play important roles in shaping national digital commerce patterns. These insights have significant implications for both theory development and policy design, suggesting new directions for research and evidence-based approaches to digital transformation strategy. While limitations remain, our research provides a foundation for continued investigation of these relationships and their implications for economic development and competitiveness in the digital age.

Declarations

Conflict of Interest:

The author declares no conflict of interest.

Ethical Approval:

This study is based on publicly available secondary data and does not require ethical approval.

Artificial Intelligence Usage

The authors acknowledge the use of AI tools for literature review organization, translation assistance (Turkish -English), grammatical enhancement, and journal formatting compliance. All AI-generated content was reviewed and validated by the author.

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Figures

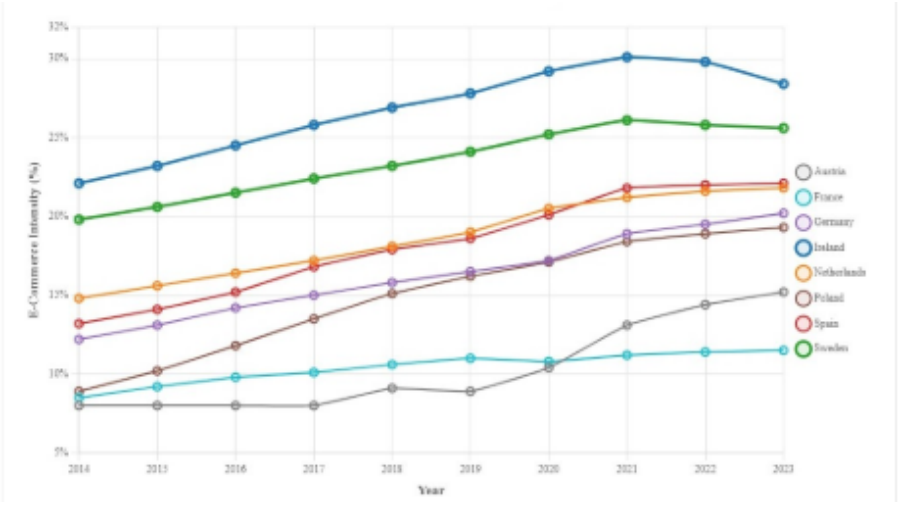


Figure 1

E-Commerce Intensity Evolution Across EU Countries (2014-2023)

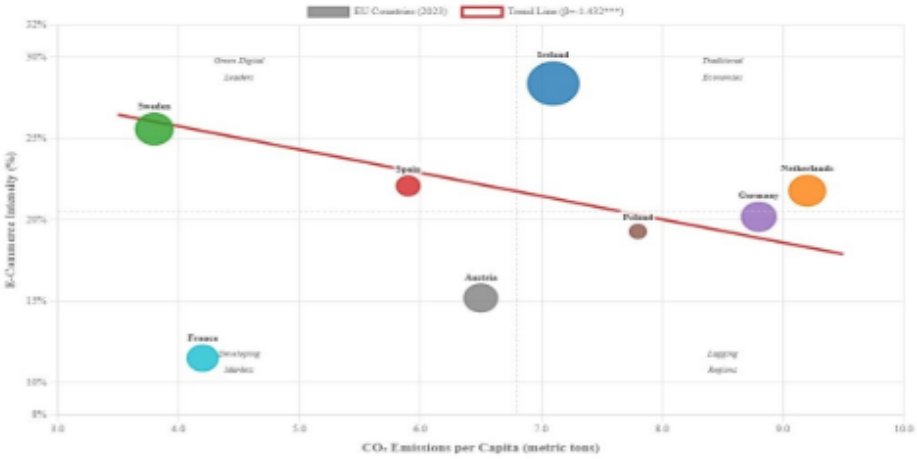


Figure 2

Environmental Consciousness and E-Commerce Nexus