

Article

Bridging Europe's Digital Divide: Macro-Digital Preconditions for Sustainable LLM Adoption in Retail

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Abstract

The deployment of large language models (LLMs) in commercial environments depends critically on the availability of robust digital infrastructure, scalable computing resources, and mature cloud architectures. This study examines how macro-level digital infrastructure, in particular cloud computing adoption, conditions the ability of the European retail sector to deploy and benefit from large language models (LLMs). Using a country-year panel of EU member states from 2017 to 2023, we estimate fixed-effects regressions to quantify the association between enterprise cloud use and retail trade volume growth, and implement an event-study design to explore dynamic responses around changes in cloud uptake. The results show that increases in cloud adoption are significantly associated with higher retail trade growth added and productivity, with especially strong effects in emerging Eastern European markets. We identify a digital threshold of around 20% of enterprises using cloud services, above which the marginal impact on retail performance becomes notably larger. These findings highlight cloud infrastructure as a key enabling condition for LLM-enabled retail applications and inform EU digital and industrial policy targeting regional digital disparities.

Keywords: large language models; cloud computing; AI systems; digital divide; retail technologies; DESI; retail sector; digital maturity; cloud adoption

1. Introduction

Digital infrastructure varies widely across Europe. In 2021, only about 41% of EU enterprises used cloud services, with adoption rates around 75% in Sweden and Finland but below 20% in several Eastern European countries [1]. This gap reflects a digital divide that can translate into uneven retail sector performance and resilience across countries.

Deploying large language models (LLMs), such as GPT-4 or LLaMA, in business environments requires robust digital infrastructure and appropriately skilled staff. However, it remains unclear whether countries with more advanced digital infrastructure actually achieve greater AI-related gains in the retail sector. We address this gap by examining whether higher national digital maturity, proxied by enterprise cloud adoption, is associated with retail sector performance over 2017–2023, and by comparing Eastern versus Western EU countries. To our knowledge, no prior study has systematically tested how cloud uptake affects retail outcomes at the macro level.

Research Significance, Gaps, and Questions

While LLM applications in retail are expanding rapidly (customer service automation, product search and recommendation, marketing content generation, and back-office analytics), their effective deployment depends on scalable compute, data pipelines, and



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enterprise IT architectures that are typically enabled by cloud infrastructure. For policy-makers and practitioners, this makes the macro-level question important: if national digital infrastructure is uneven, then the economic benefits of AI and LLM diffusion may also be uneven, potentially reinforcing existing regional productivity gaps within the EU.

Existing research provides useful but incomplete guidance for this question. First, prior studies on retail digitalisation largely focus on e-commerce, omni-channel adoption, or firm-level technology use, but do not isolate cloud adoption as a macro-level precondition for advanced AI deployment, nor do they quantify how cloud adoption correlates with retail sector performance at the country level. Second, work on AI readiness and digital maturity—often operationalised through composite indices such as DESI—documents cross-country disparities, but does not directly test whether a specific infrastructure component (enterprise cloud uptake) translates into measurable sectoral outcomes. Third, the emerging literature on LLMs in retail is dominated by technical case studies and early pilots; these studies demonstrate potential performance gains but do not address the macro-level conditions under which such gains are more likely to materialise across countries and over time.

This study contributes by linking a concrete, observable macro-digital indicator—enterprise cloud adoption—to a sector-level outcome (retail trade volume growth) in a panel of EU countries (2017–2023), explicitly testing whether the relationship differs between Eastern and Western member states. In addition, the event-study framework evaluates whether effects emerge dynamically around a meaningful adoption threshold (20%), consistent with the idea that cloud investments may initially impose adjustment costs before generating productivity benefits.

Guided by these gaps, the study addresses the following questions RQ1: Is enterprise cloud adoption associated with retail trade volume growth in EU member states? RQ2: Does this relationship differ systematically between Western and Eastern EU countries? RQ3: Do retail outcomes change dynamically around a cloud adoption threshold (20%), consistent with delayed payoffs and adjustment costs?

Digital retail (e-commerce) growth has been shown to enhance resilience during shocks, such as COVID-19 lockdowns, and to support more flexible and sustainable business models. Introducing LLMs can further improve efficiency and continuity in retail operations, but these models require substantial computing resources that are typically provided through cloud platforms. LLM readiness in this study refers to macro-level enabling conditions for LLM deployment rather than observed LLM adoption. In other words, LLM readiness is a country's capacity to support firm-level deployment of LLM applications at scale. We therefore operationalize "LLM readiness" as the availability of scalable computing and digital infrastructure that enables firms to deploy and integrate LLM-based applications, proxied in our analysis by enterprise cloud service adoption. In this framing, cloud adoption captures cross-country differences in access to scalable compute, storage, and cloud-based architectures that are commonly required for LLM deployment at scale. Survey evidence (e.g., DESI, ECB SAFE) indicates that cloud uptake is correlated with firms experimenting with generative AI and reflects broader digital capabilities, including budgets, data pipelines, and organizational processes, even though not all cloud use is AI-specific. We acknowledge the limitations of this proxy, but it offers a practical indicator of a country's digital maturity in the current data environment. A limitation is that available cross-country indicators capture overall enterprise cloud adoption rather than cloud use specifically tied to AI or GenAI workloads; future research could test whether AI-oriented cloud services drive differential effects when such data become available.

We quantify how country-level cloud computing adoption relates to retail sector growth and whether this relationship differs between Western and Eastern EU mem-

ber states. We frame this in terms of “LLM readiness,” understood as the macro-digital preconditions—such as cloud infrastructure, skills, and connectivity—that enable advanced AI use. Specifically, our objectives are to compare cloud and other digital indicators across EU countries and regions, with an emphasis on the retail sector; to analyze how these preconditions are associated with retail performance, including potential threshold effects (for example, a cloud adoption tipping point); and to discuss the implications for LLM deployment in retail and for digital policy.

Building on these gaps, this study examines whether national-level readiness for LLM adoption is associated with improved retail performance across EU member states. We operationalize LLM readiness using enterprise cloud adoption as a macro-level proxy for the digital infrastructure and data capabilities required to deploy LLM-enabled tools at scale. Using a country-level panel and an event-study design centered on reaching a critical cloud-adoption threshold, we assess not only whether outcomes improve, but also when they improve—allowing for delayed benefits consistent with adjustment-cost dynamics. The paper proceeds as follows: Section 2 reviews related literature and motivates the theoretical mechanism; Section 3 describes the data and empirical strategy; Section 4 reports the main results and robustness checks; Section 5 interprets the findings in light of the literature, discusses implications, and outlines limitations and future research.

2. Literature Review

2.1. Digitalisation and Retail Transformation

Studies show that digital infrastructure boosts retail and e-commerce adoption [2] and that digitally mature SMEs tend to be more flexible and resilient [3]. Early pilots of LLMs in retail indicate that they outperform earlier natural language processing approaches [4] suggesting that firms with strong digital capabilities, particularly in cloud and data infrastructure, may gain an AI-driven competitive edge. At the same time, some research highlights short-term adjustment costs during technology adoption: for example, implementing ERP systems or migrating to the cloud can temporarily slow performance before longer-term gains materialize [5]. Overall, however, the literature finds that greater e-commerce intensity and digitalization are positively associated with retail growth [6].

2.2. DESI and Digital Readiness Gaps

Analyses based on the Digital Economy and Society Index (DESI) show that basic infrastructure and e-government services are gradually converging across the EU, but sizeable gaps persist in digital skills and the use of advanced technologies. In general, wealthier Western member states exhibit higher levels of digital maturity [7]. Eastern EU countries, particularly post-2004 members, often lag behind in both digital skills and broadband access [8,9] reflecting a persistent East–West digital divide.

2.3. AI Readiness and Macro-Digital Preconditions

Cross-country analyses suggest that the adoption of cloud, AI, and data-driven technologies tends to boost economic performance and support more sustainable business models [10,11]. In the retail sector specifically, cloud infrastructure can streamline operations and improve scalability [12]. More broadly, digital investments enhance firms’ competitiveness [13]. For example, IoT-enabled automation in logistics and facilities management can significantly improve efficiency [14]. Taken together, these insights support the expectation of a positive link between cloud adoption and retail outcomes, as greater efficiency and flexibility should translate into higher retail performance.

2.4. East–West Digital Divide in Europe

The East–West digital gap persists: wealthier Western EU countries typically benefit more from ICT adoption, while Eastern member states face larger catch-up challenges [15,16]. There is some evidence that EU policy can mitigate these disparities; for example, Criveanu [17] finds that EU funds have boosted digital uptake more strongly in Eastern states. However, without continued targeted support, gaps in skills and infrastructure may widen further.

Few studies explicitly examine LLM deployment in a cross-country macroeconomic context, largely because systematic data on LLM adoption are still scarce. We therefore approach the question indirectly by focusing on enabling factors. A multi-country setting allows us to exploit cross-national variation that single-country case studies cannot capture. This, in turn, enables us to ask whether countries with higher digital readiness—for example, higher enterprise cloud adoption and stronger digital skills—show evidence consistent with earlier or greater uptake of LLM-like solutions in retail, as proxied by improvements in retail performance and related indicators. We also aim to inform policy: if certain digital thresholds appear to unlock significant benefits, this would support targeted investments in those areas. Conversely, if the digital divide continues to constrain outcomes, policy interventions will be needed to ensure that all regions can benefit from AI-driven innovation, in line with sustainability and inclusive growth objectives.

This paper makes three main contributions. First, it provides, to our knowledge, the first macro-level empirical evidence on how cloud computing adoption as a digital infrastructure condition is associated with retail sector performance across EU member states, with a specific focus on the preconditions for deploying LLM-based retail systems. Second, it exploits a panel-data setting with country and time fixed effects to disentangle within-country changes in cloud use from time-invariant heterogeneity, and implements an event-study design to trace dynamic responses around substantial increases in cloud adoption. Third, it identifies a non-linear, threshold-type relationship, suggesting that once enterprise cloud use surpasses around 20% of firms, the associated gains in retail value added and productivity become significantly larger, with particularly pronounced effects in Eastern European member states that are catching up digitally. The next section details the data and methodology, followed by the empirical results and analysis, and concludes with a discussion of the findings and directions for future research.

2.5. Synthesis and Positioning of This Study

Taken together, prior work suggests that digital maturity and advanced digital capabilities can improve firm resilience and performance, and that LLMs can outperform earlier NLP tools in retail tasks. However, the literature remains fragmented: retail digitalisation studies often emphasise e-commerce adoption and customer-facing technologies, AI-readiness studies typically document gaps using composite indices without linking specific infrastructure inputs to sector outcomes, and LLM studies are mostly technical demonstrations rather than macro-level evaluations. This leaves an open empirical question of whether cloud adoption—arguably a necessary enabling infrastructure for scalable LLM deployment—translates into observable differences in retail sector performance across countries, whether these effects are heterogeneous between Eastern and Western Europe, and whether benefits appear only after adoption reaches a critical mass. The present study addresses these gaps using EU panel data (2017–2023), a two-way fixed effects design, and an event-study analysis around a 20% cloud adoption threshold.

3. Materials and Methods

3.1. Data

This study employs a quantitative cross-country analysis based on secondary data from reputable institutional sources, primarily Eurostat. The dataset covers 27 EU member states over the period 2017–2023 (annual data). We focus on Europe due to data availability—Eurostat provides harmonized indicators on the digital economy and retail activity—and policy relevance, as the EU has explicit digital targets and encompasses both advanced and catching-up digital economies.

The key variables are defined as follows.

- Retail performance: Annual growth in the Retail Trade Volume Index (deflated, real terms), obtained from Eurostat’s Short-Term Statistics (base year 2015 = 100).
- Cloud adoption: The percentage of enterprises with at least 10 employees using cloud computing services, based on Eurostat surveys underlying the DESI indicators. This measure varies substantially across member states (for example, around 75% in Finland versus about 18% in Bulgaria by 2023; [18]. For each country, we identify the first year in which enterprise cloud usage exceeds 20%, which we use as the “event” threshold in our dynamic analysis.
- Other indicators (context only): For 2023–2024, we compile additional indicators that proxy for broader digital readiness, namely the share of firms using any AI technology and the share of individuals with at least basic digital skills, from Eurostat. Due to limited time coverage and missing data, these variables are not included in the core panel regressions; instead, they are used descriptively to characterize cross-country differences in digital maturity.
- Regional groupings: To capture structural differences in digital development, we classify countries into “West EU” (the EU-15) and “East EU” (the 12 newer member states that joined in or after 2004). We compare simple averages of cloud adoption, retail indicators, and other digital measures across these two groups in descriptive figures.
- Data sources: All variables are drawn from Eurostat databases or related official EU reports, ensuring harmonized definitions and comparability across member states and over time.

3.2. Empirical Strategy

The research questions require separating cross-country structural differences (e.g., baseline income levels, long-run institutional factors) from within-country changes in cloud uptake over time. Two-way fixed effects are appropriate because they absorb time-invariant country heterogeneity and common EU-wide shocks in each year, allowing identification from within-country variation. This empirical setting raises standard endogeneity concerns. Reverse causality is possible if improvements in retail performance lead firms to adopt cloud services more rapidly. Omitted time-varying country factors such as policy changes, complementary digital investments, sector composition shifts, or demand shocks could also influence both cloud uptake and retail outcomes. Our baseline specification mitigates these concerns through country and year fixed effects and controls for broader economic and digital development. We further probe robustness and timing using lagged cloud adoption, alternative specifications (including first differences), placebo tests using leads within the event-study framework, and sensitivity checks excluding 2020. While these strategies cannot fully eliminate endogeneity in the absence of an external instrument, the consistency of results across specifications increases confidence that the main patterns are not driven by short-run shocks or a single modeling assumption. To further assess timing and reduce concerns that retail growth simply predicts cloud adoption, the analysis includes robustness

checks using lagged cloud adoption and placebo leads, and it complements the TWFE estimates with an event-study design aligned on an adoption threshold that is interpretable as reaching a minimum level of digital capability needed for scalable AI/LLM deployment.

We estimate a standard two-way fixed-effects panel model in which retail performance in country i and year t is regressed on enterprise cloud adoption and a set of control variables. The baseline specification includes country fixed effects to absorb time-invariant heterogeneity (such as institutional quality, long-run consumer preferences, or structural features of the retail sector) and year fixed effects to capture common shocks (including EU-wide policy changes, macroeconomic cycles, and global events such as the COVID-19 pandemic).

Control variables include GDP per capita and the share of firms using e-commerce, which proxy for broader economic and digital development. We include e-commerce share to capture broader retail digitalization and demand-channel shifts toward online purchasing that may affect retail performance independently of enterprise cloud adoption. Controlling for e-commerce share helps separate supply-side scalable infrastructure (cloud capability) from demand-side channel composition and digital purchasing intensity. While cloud adoption and e-commerce share are related aspects of digital transformation, they capture distinct mechanisms and are jointly included to reduce omitted-variable bias in the estimated cloud coefficients. This specification allows us to interpret the estimated coefficients as within-country associations between changes in cloud adoption and changes in retail outcomes over time, conditional on these controls, while stopping short of claiming strict causality.

The baseline regression takes the form:

RetailGrowth_{it}

$$= \beta_1 \cdot \text{CloudAdoption}_{it} + \beta_2 \cdot \text{East}_i + \beta_3 \cdot (\text{CloudAdoption}_{it} \times \text{East}_i) + \beta_4 \cdot \text{ECommerceShare}_{it} + \beta_5 \cdot \text{GDPpc}_{it} + \alpha_i + \gamma_t + \varepsilon_{it} \quad (1)$$

Here, *RetailGrowth_{it}* denotes the annual growth rate of the retail trade volume index; *CloudAdoption_{it}* is the share of enterprises using cloud services; *East_i* is a dummy variable equal to 1 for Eastern EU member states and 0 otherwise; and α_i and γ_t are country and year fixed effects, respectively. Standard errors are reported in parentheses. The main coefficients of interest are β_1 , which captures the association between cloud adoption and retail growth in Western EU countries, and β_3 , which measures whether this association differs systematically in Eastern EU member states.

To investigate the dynamic pattern of retail performance around substantial increases in cloud adoption, we complement the panel regressions with an event-study analysis. We define an “event” as the first year in which a country’s enterprise cloud adoption exceeds a pre-specified threshold (set at 20% in the main specification). For each country, we normalize the retail volume index to 100 in the event year (year 0) and then compute the average index for the years $t = -2, -1, 0, +1, \dots, +5$ across all countries that cross the threshold. Plotting these average trajectories allows us to visualize how retail performance evolves before and after surpassing the cloud uptake threshold. This approach is descriptive rather than a formal causal test, but it provides useful evidence on the timing and shape of the relationship between rising cloud adoption and retail outcomes.

4. Results

Table 1 reports the baseline two-way fixed-effects (TWFE) estimates with country and year fixed effects and the core controls used throughout the manuscript. Coefficients are

interpreted as percentage-point changes in the retail outcome associated with a 1% change in enterprise cloud adoption.

Table 1. Baseline TWFE regression (key coefficients).

	Estimate (Robust SE)
Cloud adoption share	−0.365 *** (0.093)
Cloud adoption × East	0.738 *** (0.076)
E-commerce share	0.354 ** (0.170)
GDP per capita	0.001 (0.000)

Notes: Dependent variable is the retail index outcome used in the manuscript. Country and year fixed effects included. Heteroskedasticity-robust standard errors in parentheses. Significance: *** $p < 0.01$, ** $p < 0.05$.

In Western EU member states (East = 0), enterprise cloud adoption is negatively associated with retail performance. The estimated coefficient on *Cloud adoption share* is −0.365 ($p < 0.01$), implying that a 1 percentage-point increase in cloud adoption is associated with a 0.365 percentage-point decline in the retail outcome, conditional on fixed effects and controls.

The interaction term *Cloud adoption × East* is positive and statistically significant (0.738, $p < 0.01$), indicating that the cloud–retail association is substantially more positive in Eastern EU member states. Combining the main and interaction effects implies a net association in Eastern EU countries of $-0.365 + 0.738 = 0.373$ percentage points for a 1 percentage-point increase in cloud adoption.

The estimated coefficients on the controls are consistent with the descriptive patterns in the data: *E-commerce share* enters positively and is statistically significant, whereas *GDP per capita* is small and not statistically distinguishable from zero in the baseline specification.

4.1. Interpretation

In more mature Western markets, higher cloud adoption appears to be linked with marginally slower retail growth. This pattern may reflect intensified competition, greater price transparency, or saturation effects, where additional digital investments primarily redistribute demand among retailers rather than expanding the overall market. By contrast, in emerging Eastern EU markets, higher cloud use is associated with substantially faster retail growth, consistent with modernization gains such as improved IT systems, fewer stock-outs, more efficient logistics, and expanded access to e-commerce channels that raise overall retail volumes.

These core findings are robust to a range of sensitivity checks. Using lagged cloud uptake (Cloud_{t-1}) instead of contemporaneous values, estimating first-difference specifications, excluding 2020 (the main pandemic shock year), and conducting placebo tests that use future cloud values all yield a similar East–West split: a weakly negative association in Western Europe and a clearly positive one in Eastern Europe. Variance inflation factors remain low across specifications, indicating that multicollinearity is not driving the results. For brevity, the full regression tables are not reproduced here, but they consistently confirm this regional pattern.

Descriptive trends in cloud adoption mirror these regressions. As shown in Figure 1, both regions approximately doubled their enterprise cloud usage between 2017 and 2023, yet Western Europe remained ahead throughout the period. Average enterprise cloud

adoption in Western EU countries rose from about 33% in 2017 to around 53% in 2023, whereas in Eastern EU countries it increased from roughly 20% to about 42%. The absolute gap narrowed only slightly, implying that Eastern member states are catching up in proportional terms but still lag in absolute levels. The fastest early growth in Eastern Europe was observed in Poland and the Baltic states.

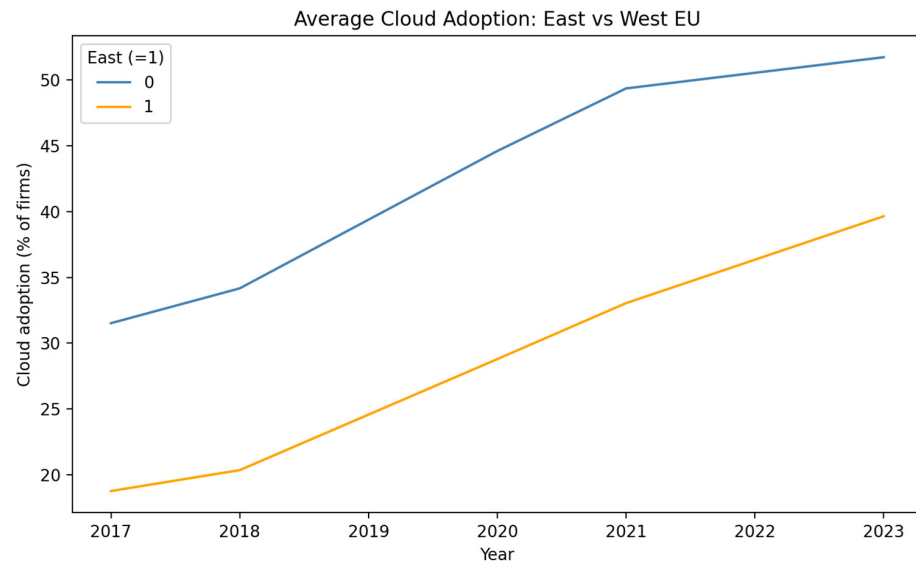


Figure 1. The trend of cloud adoption rates in Western vs. Eastern EU from 2017 to 2023.

Retail performance dynamics also differ across regions. Western EU retail volumes grew moderately and relatively smoothly, with a small decline in 2020 followed by a rebound to around +9% growth in 2022, before stabilizing thereafter. Eastern EU countries experienced more volatility: a sharper drop in 2020, followed by a surge to approximately +18% in 2022 and then a normalization to around 6–7% in 2023 (Figure 2). This pattern suggests that Western Europe’s more advanced digitalization may have contributed to greater stability, whereas Eastern Europe underwent a more pronounced boom–bust around the COVID-19 period, likely driven by a combination of pent-up demand, inflation, and structural catch-up, rather than technology alone.

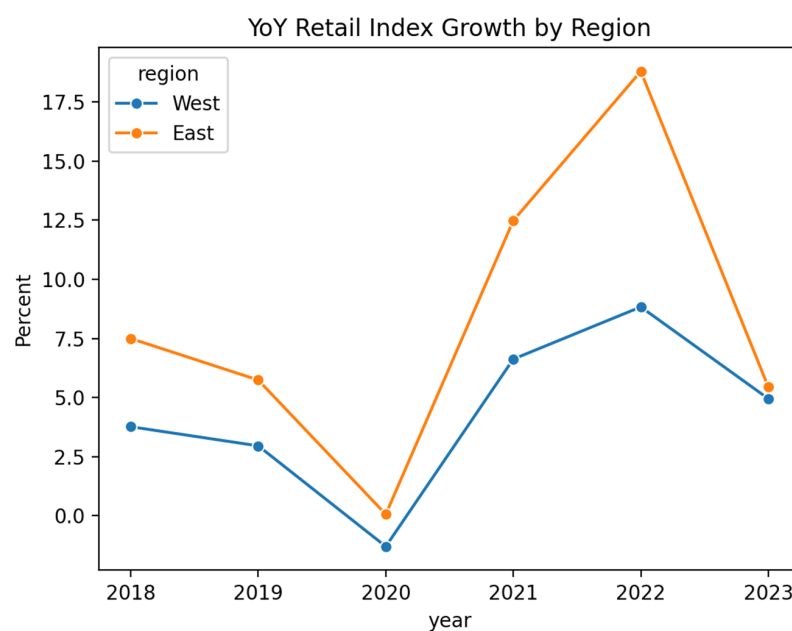


Figure 2. Retail trade YoY growth in Western vs. Eastern EU from 2017 to 2023.

4.2. Robustness Checks and Alternative Specifications

Appendix A Table A1 summarizes robustness checks designed to assess whether the baseline pattern is sensitive to reasonable alternative specifications and samples. First, we re-estimate the model excluding 2020 to assess sensitivity to the extraordinary pandemic-year disruption. Second, we use lagged cloud adoption ($t - 1$) to reduce simultaneity concerns. Third, we estimate a first-difference specification focusing on within-country changes over time. Fourth, we implement a lead placebo specification ($t + 1$), replacing current cloud adoption with next year's value; if the timing is consistent, future cloud uptake should not predict current retail performance (a falsification test). Fifth, we re-estimate the baseline on a panel dataset to ensure results are not driven by unbalanced-country coverage. Across these checks, the Western-EU cloud coefficient remains negative and statistically significant, while the Cloud $\times$ East interaction remains positive and statistically significant. The implied net cloud association in Eastern EU countries remains positive across specifications, though the magnitude attenuates in first differences. Finally, Appendix A Table A2 reports variance inflation factors (VIFs) for the baseline regressors. All VIF values are below 2, indicating limited multicollinearity among the main covariates used in the baseline model; this specifically alleviates concerns that e-commerce share is mechanically collinear with cloud adoption in our baseline specification.

4.3. Event-Study: 20% Cloud Adoption Threshold

To further explore the timing of digital adoption and retail performance, we implement an event-study analysis that aligns countries by the year in which they first cross a 20% threshold of enterprise cloud adoption. We then track the evolution of their retail trade index before and after this “event.” Figure 3 summarizes the results. In the two years prior to crossing the 20% threshold, the average retail index is relatively flat, fluctuating in a narrow band around 96–99 when expressed relative to the normalized event-year value of 100. At year 0 (the first year with cloud adoption above 20%), we set the index to 100 by construction.

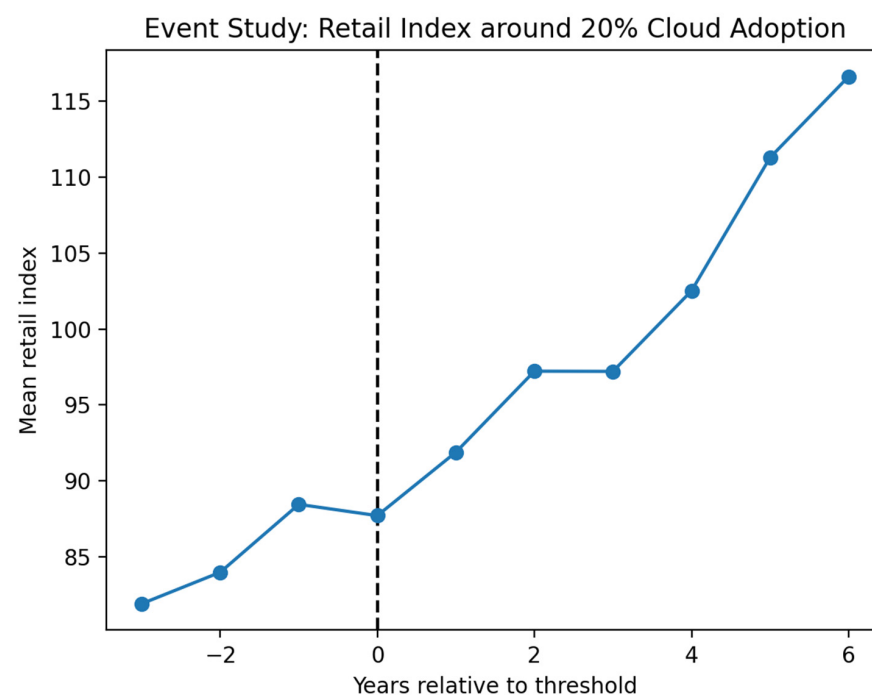


Figure 3. Retail index: 20% cloud adoption threshold.

In the 1–2 years immediately following the event, the average retail index may dip slightly, in part because several countries cross the 20% threshold around 2020, when the pandemic temporarily depressed retail activity. However, from year +2 to year +5, the average index rises steadily to around 110–115. This suggests that, on average, retail volumes grow by roughly 10–15% above the event-year baseline within five years after surpassing 20% enterprise cloud adoption. The absence of a clear positive trend in the pre-event period, combined with the subsequent acceleration, is consistent with a productivity J-curve [19], in which the benefits of digital investments materialize only after an initial adjustment phase.

Overall, higher cloud adoption—our macro-level proxy for LLM readiness—is associated with improved retail performance on average, but the relationship is strongly heterogeneous across regions. In Western Europe’s already saturated retail markets, additional cloud infrastructure appears to yield diminishing, and in some cases slightly negative, marginal returns in terms of aggregate retail growth. In contrast, Eastern Europe’s catching-up economies experience substantial gains from further cloud uptake, consistent with digital infrastructure closing structural gaps and enabling more rapid modernization. This pronounced East–West difference is the central empirical result of our analysis.

5. Discussion and Conclusions

Our findings confirm a pronounced East–West digital divide in economic outcomes. Western EU countries, which entered the period with relatively advanced digital infrastructure, experienced modest but stable retail growth and smaller COVID-19 setbacks. Eastern EU countries, where enterprise cloud use was initially much lower, exhibited more volatile retail dynamics and very strong rebound growth in 2021–2022, partly driven by post-pandemic recovery and inflation. As these one-off factors fade, there is a risk that retail growth in Eastern member states will stall unless digital infrastructure continues to improve. This pattern is consistent with prior work showing that lagging regions can converge quickly once they adopt key technologies, but that targeted support is needed to sustain this process.

The event-study analysis suggests a “tipping point” effect around 20% enterprise cloud usage. When a country’s cloud adoption crosses this approximate threshold, retail performance tends to increase in subsequent years (Figure 3). We observe no clear upward trend in retail outcomes in the pre-treatment leads, while the post-treatment coefficients indicate a marked improvement after the threshold is reached. This pattern is consistent with a “productivity J-curve,” in which firms incur adjustment costs and reorganization efforts before fully benefiting from new technologies.

Importantly, the adjustment-cost mechanism implied by the productivity J-curve may not be uniform across the EU. Countries in Eastern Europe, often starting from a lower digital baseline, may face higher initial learning, integration, and restructuring costs when adopting cloud and data-intensive practices, which could delay measurable performance effects. However, once these complementarities are in place, they may also realize larger modernization gains because the marginal returns to upgrading basic infrastructure, skills, and workflows are higher. In contrast, many Western European economies already operate closer to the technological frontier; for them, the main costs may be tied less to basic capability-building and more to deeper organizational redesign and business-model transformation, which can be complex and slower-moving. Recognizing such regional heterogeneity helps interpret cross-country differences in the timing and magnitude of post-threshold effects. Overall, the results imply that reaching a critical mass of digital infrastructure can unlock new efficiencies across the retail sector and create more favorable conditions for the deployment of LLM-enabled applications.

To move beyond a restatement of coefficients, the key question is why retail outcomes improve only after the threshold is reached. A capability-based interpretation is that cloud adoption affects performance mainly through complementary intangible investments—skills and training, data governance, systems integration, cybersecurity practices, and workflow redesign—that take time to accumulate and diffuse. In this view, the “adjustment phase” of the J-curve reflects organizational reconfiguration and learning, while the subsequent gains reflect the point at which digital infrastructure and complementary capabilities jointly enable scalable deployment of data-intensive tools, including LLM-enabled applications. The practical implication is that infrastructure adoption alone may be insufficient; complementary investments that help firms translate cloud infrastructure into operational improvements are likely decisive for realizing medium-run gains.

5.1. Discussion in Relation to Prior Literature

Findings in this paper align with prior research showing that digital maturity can support resilience and performance in retail and SMEs, but we extend this literature by isolating enterprise cloud adoption as a specific macro-level enabling input rather than relying on broad composite indices of digitalisation. In this sense, cloud diffusion can be interpreted as a prerequisite capability for data-intensive operations and scalable deployment of newer AI tools, including LLM-enabled applications.

The strong positive association in Eastern EU countries is consistent with “catch-up” dynamics frequently reported in digital transformation research, where the marginal returns to infrastructure investments are larger when baseline adoption is low. In lower-baseline settings, cloud adoption may relax binding constraints on basic capabilities—data storage and processing, interoperability, and access to scalable computing—making downstream operational improvements more feasible once complementary inputs are accumulated.

At the same time, the weaker or negative association in Western EU countries departs from the common assumption that more digitalisation always improves sector performance. One explanation is diminishing marginal returns in already digitally mature markets, where incremental cloud adoption may proxy for restructuring and transition costs—migration, vendor switching, and organisational redesign—rather than immediate productivity gains. Another explanation is that retail growth in mature markets may be constrained more by demand saturation and competitive intensity, so infrastructure upgrades alone are unlikely to translate into higher aggregate sector performance without complementary changes in skills, business models, and data governance. Consistent with both interpretations, the event-study evidence points to delayed post-threshold improvements, suggesting an adjustment phase followed by medium-run gains that fit the logic of a productivity J-curve. This interpretation helps reconcile why digital infrastructure can be associated with short-run adjustment costs yet still function as a necessary condition for medium-run performance gains.

5.2. Limitations and Future Work

This study has several limitations that should be considered when interpreting the findings. First, the empirical approach is based on an observational country-level panel and therefore cannot fully establish causality. Although the two-way fixed-effects (TWFE) specification controls for time-invariant country characteristics and common year shocks, it still relies on the assumption that remaining unobserved factors affecting retail growth are not systematically correlated with changes in cloud adoption. Time-varying omitted variables may still be present, including shifts in national retail regulation, competition dynamics, logistics modernization, consumer confidence, sectoral composition, or contemporaneous digital-policy initiatives that co-evolve with cloud uptake. In addition,

the analysis may be affected by measurement error in the cloud adoption indicator (e.g., cross-country differences in reporting, survey design, or interpretation of “cloud services”), which can attenuate estimated relationships.

Second, the theoretical framing uses enterprise cloud adoption as a macro-level precondition and proxy for LLM readiness, rather than a direct measure of actual LLM deployment intensity in retail. Cloud infrastructure is an enabling layer for scalable AI and LLM applications, but it is not equivalent to adoption of LLMs, nor does it capture organizational capabilities that shape value creation (data governance, workforce skills, change management, or integration into workflows). As a result, the estimated associations should be interpreted as evidence about macro-digital preparedness and its relationship with retail performance, not as a direct estimate of the effect of LLM implementation itself.

Third, the scope of the data imposes constraints on generalizability and on the ability to observe long-run adjustment. The sample is limited to EU member states and the period 2017–2023, which is informative for the recent digital transition but still relatively short for capturing longer-term productivity and restructuring dynamics. Moreover, the COVID-19 shock overlaps with the study window and may have influenced both the pace of digital adoption and retail volumes through exceptional and heterogeneous channels (lockdowns, supply chain disruptions, shifts from offline to online purchasing, and temporary policy support). Although the analysis includes year fixed effects and robustness checks excluding 2020, pandemic-era dynamics may still affect the timing and magnitude of the estimated responses.

Fourth, the outcome variable—retail trade volume growth—captures overall sector performance but does not isolate the specific channels through which cloud and LLM-related technologies might matter. Retail volumes may respond to many forces unrelated to AI readiness (inflation and real income dynamics, tourism flows, labor market conditions, and energy prices), and aggregate volume indicators do not reveal whether gains are driven by productivity improvements, price adjustments, margin changes, enhanced customer experience, or increased market concentration. Consequently, the study cannot directly distinguish whether observed improvements reflect efficiency gains, demand-side effects, or reallocation within the retail sector.

These limitations suggest several directions for future research. A first priority is to connect macro-level digital readiness to micro-level adoption by using firm-level or establishment-level datasets that measure cloud use alongside concrete indicators of AI/LLM deployment (e.g., use of generative AI tools, conversational agents, automated content creation, or LLM-enabled search and recommendation systems). Such data would allow researchers to test mechanisms more directly by examining outcomes such as labor productivity, inventory turnover, unit margins, price dispersion, service quality, and customer retention. Second, stronger identification strategies would be valuable. Future work could leverage quasi-experimental designs such as policy-driven shocks to cloud availability or affordability, staggered digital-subsidy rollouts, or exogenous changes in broadband and data-center capacity, implemented via difference-in-differences designs or instrumental-variable approaches. Third, additional work could integrate micro and macro perspectives by assessing whether country-level thresholds in cloud adoption translate into higher firm-level adoption intensity and whether complementarities—skills, managerial practices, and data governance—mediate the transition from infrastructure to measurable retail performance.

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Abbreviations

The following abbreviations are used in this manuscript:

AI	Artificial intelligence
DESI	Digital Economy and Society Index
EDIH	European Digital Innovation Hub Adriatic Croatia
ERP	Enterprise Resource Planning
EU	European Union
GDP	Gross Domestic Product
ICT	Information and Communication Technology
LLM	Large Language Model
NLP	Natural Language Processing

Appendix A

Table A1. Robustness checks.

Specification	Cloud (West)	Cloud $\times$ East	Net Cloud Effect in East	N	Country FE	Year FE
Baseline TWFE	−0.365 *** (0.093)	0.738 *** (0.076)	0.373 (0.090)	171	Yes	Yes
Exclude 2020	−0.408 *** (0.102)	0.790 *** (0.073)	0.383 (0.092)	147	Yes	Yes
Lag cloud ($t - 1$)	−0.392 *** (0.111)	0.779 *** (0.089)	0.387 (0.128)	146	Yes	Yes
First diff	−0.205 ** (0.093)	0.449 *** (0.133)	0.244 (0.126)	146	No	Yes
Lead placebo ($t + 1$)	−0.302 *** (0.096)	0.650 *** (0.085)	0.348 (0.092)	146	Yes	Yes
Balanced panel	−0.367 *** (0.093)	0.739 *** (0.076)	0.373 (0.090)	168	Yes	Yes

Notes: Baseline TWFE includes country and year fixed effects and the core controls used throughout the manuscript (GDP per capita and e-commerce share). “Cloud (West)” is the estimated cloud coefficient for Western EU countries (East = 0). “Net cloud effect in East” equals the linear combination Cloud (West) + Cloud $\times$ East; its standard error is computed using the delta method. Exclude 2020 removes the pandemic year. Lag cloud ($t - 1$) replaces current cloud adoption with one-year lagged cloud adoption. First diff estimates the model in first differences and includes year fixed effects. Lead placebo ($t + 1$) replaces current cloud adoption with next year’s cloud adoption to test whether future cloud uptake predicts current retail performance (falsification test). Balanced panel restricts the sample to countries observed in all years. Standard errors are reported in parentheses. Significance: ** $p < 0.05$, *** $p < 0.01$.

Table A2. Multicollinearity diagnostics (VIF).

Variable	VIF
cloud_share	1.78
gdp_pc	1.58
ecommerce_share	1.55
cloud_x_east	1.36

Notes: VIFs computed on the pooled regressor matrix for the baseline controls and key regressors; fixed effects are not included in VIF calculation. Values below common thresholds (e.g., 5 or 10) indicate limited collinearity.

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