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CUSTOMER DIGITAL TRANSFORMATION AND SUPPLY CHAIN INFORMATION EFFICIENCY: EVIDENCE FROM THE BULLWHIP EFFECT

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Abstract: *This study examines whether customer-side digital transformation is associated with higher supply chain information efficiency in supplier–customer relationships among Chinese listed companies. The bullwhip effect is used as a relationship-level reverse proxy for demand information distortion. A quantitative archival-data design is adopted using supplier–customer-year observations from Chinese listed companies. Customer digital transformation is measured through an annual-report-based digital transformation indicator. Ordinary least squares regressions with industry and year fixed effects are estimated, with standard errors clustered at the supplier-firm level. Robustness checks use a logged bullwhip-effect measure, an alternative digital transformation indicator, supplier fixed effects, and an alternative dependent variable. Heterogeneity analysis is conducted according to external uncertainty. Customer digital transformation is negatively and significantly associated with the bullwhip effect, indicating lower demand information distortion in relationships involving digitally transformed customer firms. The association remains supported across the logged dependent-variable specification, the alternative digital transformation measure, and supplier fixed effects, although the evidence is weaker when upstream supply-demand deviation is used as the alternative outcome. The negative association is more pronounced under high external uncertainty. The findings suggest that customer-side digitalisation may generate supply-chain-level information spillovers by improving visibility, traceability, and credibility of demand-related information. The study contributes by positioning the bullwhip effect as an observable relationship-level indicator of supply chain information efficiency and by clarifying the boundary role of external uncertainty.*

Keywords: *Digital transformation; Bullwhip effect; Supply chain information efficiency; Supplier-customer relationships; Information friction*

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Introduction

In contemporary supply chains, the central managerial problem is no longer only whether products can be produced and delivered, but whether demand-related information can move across organisational boundaries without distortion. Global value chains remain a major organising structure of trade and production, while recent macro-level research emphasises that technological change, digital services, and shifting forms of value-chain participation are rewiring how firms coordinate across borders and sectors (World Bank, 2020; World Trade Organization et al., 2025). At the same time, the digital economy has become a strategic policy and business priority. The OECD Digital Economy Outlook 2024 documents the continuing expansion of digital technologies and their implications for firms, markets, and governance (OECD, 2024), while UNCTAD (2024) stresses that digitalisation must be understood as a broad economic transformation rather than a narrow technological upgrade. In China, the national digital economy plan has explicitly promoted industrial digital transformation and the use of data as a production factor (State Council of the People's Republic of China, 2022). These developments make supply chain information efficiency a substantive research issue rather than a purely operational detail.

The importance of this issue becomes clear when the downstream side of a supply chain is considered. Suppliers rarely observe final demand directly. Instead, they rely on customer-side orders, inventory adjustments, forecasts, delivery requirements, transaction records, and settlement conditions when arranging production, inventory, and fulfilment. When such information is delayed, incomplete, strategically filtered, or difficult to verify, suppliers may over-adjust production or hold excessive inventory. The operational symptom of this problem is the bullwhip effect, defined as the amplification of demand variability as orders move upstream in a supply chain (Lee et al., 1997; Shan et al., 2014; Osadchiy et al., 2021). Although the bullwhip effect is often treated as an inventory or production fluctuation problem, its deeper theoretical meaning lies in information distortion. A lower bullwhip effect can therefore be interpreted as a signal of more efficient demand information transmission between customers and suppliers.

Digital transformation offers a plausible route through which this information problem may be mitigated. Information-processing theory argues that organisations facing uncertainty need greater information-processing capacity to coordinate decisions and reduce ambiguity (Galbraith, 1973; Tushman & Nadler, 1978). Digital transformation strengthens such capacity by improving data collection, information integration, transaction traceability, operational visibility, and decision support. In listed-company research, digital transformation is commonly measured through annual-report disclosures that capture digital technologies, applications, and business practices (Wu et al., 2021; Zhao et al., 2021). In supply chain relationships, however, customer-side digitalisation is not only an internal firm capability. It may also operate as a downstream information-governance condition that affects the information environment faced by upstream suppliers.

Recent research has begun to document digital transformation spillovers along supply chains. Studies show that digitalisation can travel through vertical partnerships and affect supplier innovation, audit risk, collaboration, enterprise growth, and other inter-firm outcomes (Geng et al., 2024; B. Li et al., 2024; L. Li et al., 2024; Yang et al., 2022; Zhang & Li, 2024). More directly, Q. Li et al. (2023) report that customer digital transformation can improve the inter-

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firm information environment and reduce bullwhip effects in supply chains. Liu et al. (2025) and Sun et al. (2025) further link digital transformation with lower bullwhip-effect distortion, while Huang et al. (2026) connect customer digital transformation, bullwhip-effect mitigation, and supplier-side behavioural outcomes. This literature establishes an important foundation, but it also creates a sharper research question: if customer digitalisation has already been recognised as supply-chain relevant, how should its information-efficiency implication be theorised and empirically positioned?

The present study responds to that question by developing a focused supply chain information-efficiency interpretation of customer-side digitalisation. The latest literature review identifies three unresolved gaps. The digital transformation literature still tends to privilege firm-level outcomes, such as productivity, innovation, capital-market response, or risk evaluation, while relationship-level information outcomes remain less developed. Bullwhip-effect research has long recognised demand amplification, but the bullwhip effect is still underused as a direct relationship-level proxy for supply chain information efficiency. Information-sharing research explains why information matters for bullwhip-effect mitigation, but it often pays less attention to the costs of searching for and verifying customer information under uncertainty (Al-Sukhni & Migdalas, 2025; Liu et al., 2025; Sun et al., 2025; Huang et al., 2026). These gaps motivate a narrower and more defensible research positioning: the study does not claim that the main association is wholly new; rather, it reframes the association between customer digital transformation and the bullwhip effect as a relationship-level information-efficiency issue.

Accordingly, the purpose of this study is to examine whether customer digital transformation is associated with lower bullwhip effects in supplier–customer relationships among Chinese listed companies. Customer digital transformation is conceptualised as the downstream firm's digitalisation condition, while the bullwhip effect is treated as an observable reverse proxy for supply chain information efficiency. The theoretical logic is that digitally transformed customer firms may provide more visible, timely, traceable, and credible demand-related information, thereby reducing suppliers' information search and verification difficulties.

The study makes a focused contribution to supply chain management and digital transformation research. It shifts attention from digital transformation as an internal capability to customer-side digitalisation as a supply-chain-level information condition. It also repositions the bullwhip effect as a relationship-level indicator of information inefficiency, thereby linking digitalisation, information friction, and demand distortion in one empirical framework. The paper proceeds as follows. Section 2 reviews the relevant literature. Section 3 develops the theoretical foundations and research hypothesis. Section 4 explains the data, measures, model specification, and analysis procedure. Section 5 reports the empirical results. Section 6 discusses the theoretical and practical implications, limitations, future research directions, and concluding remarks.

Literature Review

Digital Transformation and Supply Chain Information Spillovers

Digital transformation has become a central explanation for how firms improve information processing, operational coordination, and decision support. In listed-company research, it is commonly operationalised through annual-report disclosures that capture digital technologies,

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digital applications, and digital business practices (Wu et al., 2021; Zhao et al., 2021). This firm-level literature has produced useful evidence on productivity, innovation, market valuation, and operational upgrading. However, a purely firm-centred view is incomplete for supply chain research because supply chains are interdependent information systems. Demand signals, transaction records, inventory movements, delivery requirements, and settlement conditions move across organisational boundaries and shape the decisions of upstream and downstream partners.

Recent research has therefore shifted attention from internal digital-transformation outcomes to supply-chain spillover effects. Digitalisation may travel through vertical partnerships and influence supplier innovation, audit risk, collaboration, enterprise growth, production-marketing integration, and other inter-firm outcomes (Yang et al., 2022; Geng et al., 2024; L. Li et al., 2024; B. Li et al., 2024; Zhang & Li, 2024). This stream is important because it treats digital transformation not only as an internal firm capability but also as a condition that can reshape information quality and coordination across firm boundaries. Yet much of the evidence still explains spillovers through broad firm-level consequences, such as innovation, audit fees, growth, productivity, or strategic behaviour. Relationship-level information outcomes remain less developed, especially outcomes that directly indicate whether customer-side information is transmitted to suppliers with less distortion.

The present study is positioned within this narrower gap. It examines customer digital transformation as a downstream information condition and uses the bullwhip effect as a measurable relationship-level expression of supply chain information inefficiency. This positioning avoids overstating the novelty of the main association and instead clarifies the information-efficiency meaning of customer-side digitalisation in supplier–customer relationships.

Bullwhip Effect and Information Distortion

The bullwhip effect is a foundational concept in supply chain management. Lee et al. (1997) define it as the amplification of demand variability as orders and information move upstream in a supply chain. Their classic explanation shows that demand signal processing, order batching, price variation, and rationing behaviour can distort upstream decisions. Empirical research confirms that bullwhip effects can be observed in Chinese supply chains (Shan et al., 2014), while network-based research further shows that the phenomenon should not be restricted to simple linear chains because supplier–customer relationships are embedded in broader supply networks (Osadchiy et al., 2021).

Although the bullwhip effect is often discussed as an inventory, order, or production fluctuation problem, its theoretical meaning is broader. At its core, it reflects demand information distortion across organisational boundaries. A higher bullwhip-effect value indicates that upstream responses deviate more strongly from downstream demand signals, whereas a lower value indicates more stable information transmission and better supply-demand coordination. Treating the bullwhip effect only as an operational volatility indicator therefore underplays its value as an observable relationship-level manifestation of supply chain information inefficiency.

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Recent studies strengthen this information-based interpretation. A systematic review by Al-Sukhni and Migdalas (2025) shows that information-sharing factors remain central to bullwhip-effect mitigation. Liu et al. (2025) find that digital transformation is associated with lower firm-level bullwhip effects, and Sun et al. (2025) provide further evidence that digital transformation can alleviate bullwhip-effect distortion in Chinese listed companies. These studies establish that digitalisation and information sharing are relevant to bullwhip-effect reduction, but they leave room for a more focused relationship-level interpretation. The issue is not only whether digital transformation improves general performance; it is whether customer-side digitalisation is associated with lower inter-firm information distortion.

The most recent literature has further moved the bullwhip-effect discussion toward digitalisation and information governance. Al-Sukhni and Migdalas (2025) show that information-sharing factors remain central to bullwhip-effect mitigation, indicating that the bullwhip effect is closely connected with the quality, timeliness, and usability of inter-firm information transmission. Liu et al. (2025) provide firm-level evidence that digital transformation can mitigate the bullwhip effect, while Sun et al. (2025) similarly link digital transformation with lower bullwhip-effect distortion among Chinese listed companies. Huang et al. (2026) extend this line of research by showing that customer digital transformation may shape supplier-side behavioural outcomes through the bullwhip-effect channel. Taken together, these studies justify the present paper's narrower focus on customer-side digitalisation, relationship-level information efficiency, and the bullwhip effect as an observable proxy for inter-firm demand information distortion.

Research Gap and Positioning

The reviewed literature reveals three connected gaps. The digital transformation literature has increasingly recognised supply-chain spillovers, but it still tends to emphasise broad firm-level outcomes rather than relationship-level information efficiency. Bullwhip-effect research has long recognised demand amplification, but the bullwhip effect is still underused as a direct reverse proxy for information efficiency in supplier–customer relationships. Information-sharing research explains why information matters for mitigating bullwhip effects, but it pays less attention to the costs of searching for and verifying customer-side information under uncertainty.

This study addresses these gaps by connecting three research streams that are often examined separately: digital transformation spillovers, bullwhip-effect information distortion, and supplier–customer information friction. The research does not claim that customer digital transformation is the sole determinant of the bullwhip effect. Instead, it examines whether customer-side digitalisation represents a meaningful downstream information-governance condition associated with lower demand information distortion. This bounded positioning supports a focused empirical contribution and provides the basis for the hypothesis developed in the next section.

Theoretical Foundations and Hypothesis Development

Information Processing and Downstream Information Governance

Information processing theory argues that organisations facing uncertainty and task complexity must develop sufficient information-processing capacity to coordinate decisions and reduce

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ambiguity (Galbraith, 1973; Tushman & Nadler, 1978). This logic is directly relevant to supplier–customer relationships. Suppliers often do not observe final demand directly; they rely on customer-side orders, forecasts, inventory adjustments, delivery requirements, transaction records, and payment conditions when making production and inventory decisions. If customer-side information is incomplete, delayed, or difficult to verify, suppliers may respond to noise rather than actual demand.

Customer digital transformation can increase downstream information-processing capacity by making demand-related information more structured, timely, traceable, and communicable. Digitalised systems can improve order visibility, fulfilment tracking, inventory transparency, transaction record consistency, and operational commitment credibility. In this sense, customer digital transformation should be treated as downstream information governance rather than as a generic internal technological upgrade. This interpretation is supported by evidence that customer digital transformation is associated with improved inter-firm information environments and lower bullwhip effects (Q. Li et al., 2023), reduced supplier-side audit risk and costs (L. Li et al., 2024), and supplier behavioural outcomes through the bullwhip-effect channel (Huang et al., 2026).

The theoretical value of this interpretation lies in shifting the focus from whether digital firms perform better to whether digitally transformed customers provide a clearer information environment for upstream suppliers. Customer firms occupy a distinctive informational position because they are closer to downstream demand and control key signals related to orders, forecasts, delivery requirements, and transaction commitments. Their digital transformation may therefore affect the quality of information available to suppliers, even when suppliers' own digital capabilities are not the central object of analysis.

Information Friction, External Uncertainty, and Hypothesis Development

Information friction provides a more specific explanation for the expected association between customer digital transformation and the bullwhip effect. Information economics suggests that information is costly to search for, compare, and interpret (Stigler, 1961). Transaction cost economics further indicates that uncertainty and information asymmetry increase the difficulty of verifying exchange conditions and governing inter-organisational transactions (Williamson, 1985). In supplier–customer relationships, these problems appear as information search costs and information verification costs. Search costs arise when suppliers must identify and interpret relevant customer-side demand, transaction, and operational signals. Verification costs arise when suppliers must assess whether the information received from customers is accurate, credible, and actionable.

Customer digital transformation may reduce both forms of friction. It can lower search costs by making orders, demand changes, fulfilment progress, inventory movements, and transaction records more visible and structured. It can lower verification costs by improving traceability and credibility through digitalised transaction histories, operational records, platform-supported information trails, and comparable disclosure practices. Evidence that digital transformation improves information comparability and transparency (Nie et al., 2022), together with supply-chain evidence on lower supplier-side risks and costs (L. Li et al., 2024), supports this information-friction interpretation.

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External uncertainty sharpens this logic. Under relatively stable conditions, suppliers may rely on historical routines, repeated transactions, or informal knowledge to interpret customer demand signals. Under high uncertainty, these routines become less reliable, and the value of accurate, traceable, and timely customer-side information increases. Customer digital transformation is therefore expected to be more relevant when information friction is more severe. This boundary logic is treated cautiously because information search cost and verification cost are not directly measured in this study; they are theoretical channels rather than formally tested mediators.

The bullwhip effect is an appropriate outcome for this theoretical argument because it captures the operational manifestation of information distortion. If customer digital transformation is associated with clearer and more verifiable demand information, upstream suppliers should face less ambiguity when adjusting production and inventory. Lower ambiguity should reduce excessive amplification of downstream demand fluctuations. Because the bullwhip effect is used as a reverse proxy for supply chain information efficiency, a negative association between customer digital transformation and the bullwhip effect would be consistent with the argument that digitally transformed customers are linked to lower demand information distortion in supplier–customer relationships.

H1: Customer digital transformation is negatively associated with the bullwhip effect in supplier–customer relationships among Chinese listed companies.

This hypothesis specifies an empirically testable association rather than a definitive causal effect. It is grounded in information processing theory, information economics, transaction cost reasoning, and supply chain research on digital transformation and the bullwhip effect. The contribution of this theoretical framework is to connect customer-side digitalisation with supplier–customer information efficiency while maintaining a clear boundary between theoretical channels and directly observed empirical tests.

Methodology

Research Design and Methodological Rationale

This study adopts a quantitative archival-data research design to examine whether customer digital transformation is associated with supply chain information efficiency in supplier–customer relationships among Chinese listed companies. The design is deductive because the hypothesis is derived from information-processing theory, supply chain information distortion research, and the digital-transformation spillover literature before being examined with structured secondary data. It is archival because the empirical variables are drawn from listed-company disclosures and replication datasets rather than from interviews, field observations, or self-reported survey responses.

The methodological choice follows the logic of cross-sectional and panel-data econometrics, where regression models are used to estimate conditional associations after controlling for observable characteristics and fixed sources of heterogeneity (Wooldridge, 2010; Angrist & Pischke, 2009). Because the purpose of the study is to assess whether customer-side digitalisation is systematically related to lower information distortion in supplier–customer-

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year observations, an archival regression design provides a transparent and replicable empirical strategy.

Data Source, Sample Construction, and Unit of Analysis

The empirical analysis uses secondary data from the replication dataset associated with Enterprise Digital Transformation and Information Spillover Effects: Empirical Evidence from a Supply Chain Perspective (Q. Li et al., 2023; Pipixia Team, 2023). The source data are suitable for the present study because they contain matched supplier–customer relationship information, customer digital transformation indicators, the bullwhip-effect measure, upstream supply-demand deviation, external uncertainty, customer concentration, turnover-related variables, firm size, operating performance, audit quality, ownership concentration, and managerial duality.

The unit of analysis is the supplier–customer-year relationship. In the cleaned dataset, the supplier firm is identified by up_id, the customer firm is identified by down_id, and the year variable identifies the observation period. This relationship-level structure is essential because the theoretical argument concerns information transmission from the customer side to the supplier side, rather than the internal performance of a single firm-year observation. Customer digital transformation is measured at the customer-firm side, while the bullwhip effect captures information distortion in the supplier–customer relationship.

The sample construction follows a transparent listwise screening procedure. The initial supplier–customer-year dataset contains 5,758 observations. The sample is restricted to direct supplier–customer relationships, leaving 5,140 observations. Observations with missing values for the dependent variable, bullwhip, are excluded, leaving 4,656 observations. After observations with missing control variables are removed, the final regression sample contains 4,556 supplier–customer-year observations. The usable analytical period reflects variable availability, lagged measurement, and listwise deletion rather than only the nominal coverage of the source data.

Table 1 summarises the sample construction procedure and clarifies the final supplier–customer-year regression sample.

Table 1: Sample Construction

Sample selection procedure	Observations
Initial supplier-customer-year observations	5,758
Direct supplier-customer relationships retained	5,140
Observations with missing bullwhip effect excluded	4,656
Observations with missing control variables excluded	4,556
Final regression sample	4,556

Note. The final regression sample consists of supplier–customer-year observations. The screening procedure retains direct supplier–customer relationships and excludes observations with missing values in the dependent variable or control variables.

Measurement of Variables

Supply chain information efficiency is proxied by the bullwhip effect. The bullwhip effect is a foundational supply chain measure that captures the amplification of demand variability as information moves upstream (Lee et al., 1997; Shan et al., 2014). In this study, it is treated as

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a reverse proxy for information efficiency because larger values indicate stronger demand information distortion and weaker supply-demand coordination. The measurement logic follows empirical bullwhip-effect research that uses the ratio between supplier-side supply-demand deviation and customer-side supply-demand deviation to capture relationship-level information distortion (Q. Li et al., 2023). AR_supply, which captures upstream supplier supply-demand deviation, is used as an alternative dependent variable in robustness analysis.

The main independent variable is customer digital transformation (CDT). In the original cleaned dataset, this variable is labelled did; however, this paper reports it as CDT to avoid confusion with a difference-in-differences design. CDT represents a customer-firm digital transformation indicator constructed from listed firms' annual-report information. The measurement is grounded in the annual-report text-analysis approach developed in Chinese listed-company digital transformation research. An alternative customer digital transformation indicator, CDT_sub, originally labelled did_sub in the source dataset, is also used to examine measurement robustness.

The control variables are selected to account for observable firm and supply-chain conditions that may be associated with the bullwhip effect and supply-demand deviation. These variables include operating performance, firm size, managerial duality, customer concentration, external uncertainty, ownership concentration, accounts receivable turnover days, accounts payable turnover days, inventory turnover days, and audit quality. Industry and year fixed effects are included to reduce unobserved heterogeneity across industries and periods.

Model Specification and Estimation Strategy

The baseline empirical model estimates the conditional association between customer digital transformation and the bullwhip effect using ordinary least squares regression with industry and year fixed effects. The specification is not designed as a causal identification strategy; rather, it evaluates whether customer-side digitalisation is systematically associated with lower information distortion after controlling for observable characteristics and fixed industry-year conditions. The specification can be expressed as follows:

$$Bullwhip(s,c,t) = \alpha + \beta_1 CDT(c,t) + \gamma Controls(s,c,t) + IndustryFE + YearFE + \varepsilon(s,c,t)$$

In this equation, *Bullwhip(s,c,t)* denotes the bullwhip effect for supplier firm *s*, customer firm *c*, and year *t*. *CDT(c,t)* denotes the customer firm's digital transformation indicator, and *Controls(s,c,t)* represents the set of control variables. *Industry FE* and *Year FE* denote industry and year fixed effects. The coefficient of interest is β_1. A negative coefficient is consistent with the theoretical expectation that customer digital transformation is associated with lower information distortion in supplier–customer relationships.

Standard errors are clustered at the supplier-firm level. This choice is methodologically important because supplier–customer-year observations involving the same supplier may not be statistically independent. Clustered standard errors are widely recommended when residuals may be correlated within groups, because conventional standard errors can overstate estimator precision under within-cluster dependence (Petersen, 2009; Cameron & Miller, 2015). Supplier-level clustering is also consistent with the supplier-side interpretation of the dependent variable.

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Robustness, Heterogeneity, and Analytical Procedure

The data analysis follows a sequential procedure. The dataset is screened to retain direct supplier–customer-year relationships and remove observations with missing values in the dependent variable and controls. The final analytical sample is then described through descriptive statistics, including means, standard deviations, minimum values, medians, and maximum values. Pairwise correlations are examined to provide preliminary information about the relationships among the main variables and selected controls. These descriptive and correlation procedures are consistent with standard multivariate data-analysis practice (Hair et al., 2019).

The hypothesis is tested through the baseline fixed-effects regression. Robustness analyses are then conducted to assess the sensitivity of the main association, not to establish definitive causality. The dependent variable is transformed into ln(1 + Bullwhip) to reduce the influence of the right-skewed distribution of the bullwhip effect. The main digital transformation indicator is replaced with CDT_sub to examine sensitivity to an alternative measurement specification. Supplier fixed effects are introduced to account for time-invariant supplier-level heterogeneity. AR_supply is used as an alternative dependent variable to examine whether the direction of the association is similar when a broader upstream supply-demand deviation measure is used. Because AR_supply captures a wider supply-demand deviation outcome than the relationship-level bullwhip measure, weaker evidence in this specification is treated as a boundary condition rather than as a failure of the main research logic.

Heterogeneity analysis is conducted based on external uncertainty. The sample is divided into high- and low-uncertainty groups using the median value of lnuncertainty. This analysis is theoretically motivated by the information-friction argument: when uncertainty is higher, suppliers face greater difficulty in interpreting and verifying demand-related information, so customer digital transformation may be more relevant for reducing information distortion. The heterogeneity test is interpreted as boundary-condition evidence that is consistent with an information-friction explanation. It is not treated as a formal mediation test because information search cost and verification cost are not directly observed in the dataset.

Methodological Transparency and Reproducibility

The methodology is designed to preserve transparency, reproducibility, and interpretive caution. The study uses secondary archival data and observable variables, which reduces concerns associated with common method bias in self-reported survey research. At the same time, archival data do not eliminate endogeneity concerns. Reverse causality, omitted variables, and unobserved relationship-specific factors may remain. For this reason, the empirical findings are interpreted as conditional associations rather than definitive causal effects.

The analytical workflow can be summarised as follows: data import and cleaning; supplier–customer-year sample construction; variable identification and measurement verification; descriptive statistics; correlation analysis; baseline OLS regression with industry and year fixed effects; robustness checks using alternative dependent-variable transformations, alternative independent-variable measurement, and supplier fixed effects; and heterogeneity analysis based on external uncertainty. This workflow aligns the theoretical argument, archival measurement, and regression-based empirical strategy.

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Results

Descriptive Statistics

Table 2 presents the descriptive statistics for the final regression sample. The final sample contained 4,556 supplier–customer-year observations. The dependent variable, bullwhip, had a mean of 1.8780, a standard deviation of 3.5820, a minimum value of 0.0296, a median value of 1.0081, and a maximum value of 32.3091. The alternative dependent variable, AR_supply, had a mean of 1.6676 and a standard deviation of 2.0985. The main digital transformation indicator, CDT, had a mean of 0.2902 and a standard deviation of 0.4539. The alternative digital transformation indicator, CDT_sub, had a mean of 0.5151 and a standard deviation of 0.4998.

For the control variables, ROA had a mean of 0.0419 and a standard deviation of 0.0578. Firm size, measured by size, had a mean of 23.0584 and a standard deviation of 1.7395. CustomerConcentration had a mean of 26.9600 and a standard deviation of 22.3092. External uncertainty, measured by lnuncertainty, had a mean of 4.1381 and a standard deviation of 0.5110. The turnover-related variables, LnArDays, LnApDays, and LnInvDays had mean values of 3.5603, 4.2459, and 4.2990, respectively. The complete descriptive statistics are shown in Table 2.

Table 2. Descriptive Statistics

Variable	N	Mean	SD	Min	Median	Max
bullwhip	4,556	1.8780	3.5820	0.0296	1.0081	32.3091
AR_supply	4,556	1.6676	2.0985	0.1046	1.1229	18.6906
CDT	4,556	0.2902	0.4539	0.0000	0.0000	1.0000
CDT_sub	4,556	0.5151	0.4998	0.0000	1.0000	1.0000
ROA	4,556	0.0419	0.0578	-0.2176	0.0376	0.2500
size	4,556	23.0584	1.7395	19.8188	22.7516	28.4052
Duality	4,556	0.2030	0.4012	0.0000	0.0000	1.0000
CustomerConcentration	4,556	26.9600	22.3092	0.1900	20.0000	99.4800
lnuncertainty	4,556	4.1381	0.5110	2.8332	4.2341	5.4337
Top	4,556	0.3808	0.1695	0.0714	0.3588	0.8635
LnArDays	4,556	3.5603	1.3692	0.1198	3.7735	6.2262
LnApDays	4,556	4.2459	0.7755	1.6156	4.2843	6.1641
LnInvDays	4,556	4.2990	1.0735	0.6029	4.2759	7.5484
Audit	4,556	0.1512	0.3583	0.0000	0.0000	1.0000

Note. bullwhip is the main dependent variable. CDT is the main customer digital transformation indicator. AR_supply is used as an alternative dependent variable in robustness analysis.

Correlation Analysis

Table 3 reports the pairwise correlations among the selected variables used in the empirical analysis. The correlation between CDT and bullwhip was -0.048. The correlation between CDT_sub and bullwhip was -0.083. The correlation between AR_supply and bullwhip was 0.608. The correlation between CDT and CDT_sub was 0.618.

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Among the control variables reported in Table 3, CustomerConcentration was correlated with bullwhip at -0.030, lnuncertainty was correlated with bullwhip at -0.014, and LnInvDays was correlated with bullwhip at 0.096. The complete correlation matrix is shown in Table 3.

Table 3. Correlation Matrix

Variable	bullwhip	AR_supply	CDT	CDT_sub	ROA	size	Customer Concentration	lnuncertainty	Top	LnInvDays
bullwhip	1.000									
AR_supply	0.608	1.000								
CDT	-0.048	-0.051	1.000							
CDT_sub	-0.083	-0.091	0.618	1.000						
ROA	0.012	0.007	-0.005	-0.041	1.000					
size	-0.004	0.029	0.013	0.062	0.031	1.000				
Customer Concentration	-0.030	-0.037	-0.048	-0.041	-0.097	-0.148	1.000			
lnuncertainty	-0.014	-0.015	0.193	0.213	-0.026	0.388	-0.041	1.000		
Top	-0.034	0.013	-0.062	-0.017	-0.032	0.414	-0.005	0.128	1.000	
LnInvDays	0.096	0.152	-0.007	-0.044	-0.078	-0.183	-0.003	-0.038	-0.137	1.000

Note. The table reports pairwise correlations for selected main variables. Correlations are descriptive and should not be interpreted as causal evidence.

Baseline Regression Results

Table 4 reports the baseline regression results. Model 1 included industry and year fixed effects without control variables. The coefficient of CDT was -0.2715, with a clustered standard error of 0.1213, and was statistically significant at the 5 percent level. The adjusted R-squared value was 0.0664.

Model 2 included the full set of control variables, industry fixed effects, and year fixed effects. The coefficient of CDT was -0.2846, with a clustered standard error of 0.1251, and was statistically significant at the 5 percent level. The adjusted R-squared value was 0.0723. Among the control variables, the coefficient of Audit was -0.5917 and statistically significant at the 5 percent level. The coefficient of LnInvDays was 0.2991 and statistically significant at the 1 percent level.

Model 3 replaced CDT with the alternative digital transformation indicator, CDT_sub. The coefficient of CDT_sub was -0.2710, with a clustered standard error of 0.1190, and was statistically significant at the 5 percent level. The adjusted R-squared value was 0.0724. In this model, Audit remained statistically significant at the 5 percent level, and LnInvDays remained statistically significant at the 1 percent level. The complete baseline regression results are shown in Table 4.

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Table 4. Baseline Regression Results

Variable	(1) Digital indicator no controls	(2) Digital indicator + controls	(3) Alternative digital indicator
CDT	-0.2715** (0.1213)	-0.2846** (0.1251)	
CDT_sub			-0.2710** (0.1190)
Audit		-0.5917** (0.2594)	-0.5941** (0.2600)
ROA		0.1265 (1.0310)	0.1237 (1.0257)
size		0.1100 (0.0693)	0.1116 (0.0698)
Duality		0.0284 (0.1959)	0.0327 (0.1950)
CustomerConcentration		-0.0075 (0.0046)	-0.0076* (0.0046)
lnuncertainty		0.0702 (0.1995)	0.0697 (0.2006)
Top		0.2468 (0.6179)	0.2526 (0.6155)
LnArDays		0.0996 (0.0722)	0.1021 (0.0722)
LnApDays		-0.0308 (0.1179)	-0.0275 (0.1189)
LnInvDays		0.2991*** (0.0959)	0.2918*** (0.0965)
Industry FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Controls	No	Yes	Yes
Clustered SE	Supplier firm	Supplier firm	Supplier firm
Observations	4,556	4,556	4,556
Adjusted R-squared	0.0664	0.0723	0.0724

Note. The dependent variable is bullwhip. Robust standard errors clustered at the supplier-firm level are reported in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

Robustness Checks

Table 5 reports the robustness checks. In the baseline specification, the coefficient of CDT was -0.2846, with a clustered standard error of 0.1251 and a p-value of 0.023. When the dependent variable was transformed into ln_bullwhip, the coefficient of CDT was -0.0461, with a clustered standard error of 0.0210 and a p-value of 0.028.

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When the alternative digital transformation indicator CDT_sub was used, the coefficient was -0.2710, with a clustered standard error of 0.1190 and a p-value of 0.023. When supplier fixed effects and year fixed effects were included, the coefficient of CDT was -0.3564, with a clustered standard error of 0.1442 and a p-value of 0.013. When AR_supply was used as the alternative dependent variable, the coefficient of CDT was -0.0621, with a clustered standard error of 0.0631 and a p-value of 0.325. This alternative-outcome specification therefore produced weaker evidence than the main bullwhip-effect specification. The complete robustness results are reported in Table 5.

Table 5. Robustness Checks

Model	Dependent variable	Main X	Coefficient	Clustered SE	p-value	N	Fixed effects
R1 Baseline	bullwhip	CDT	-0.2846**	0.1251	0.023	4,556	Industry FE + Year FE
R2 Logged DV	ln_bullwhip	CDT	-0.0461**	0.0210	0.028	4,556	Industry FE + Year FE
R3 Alternative X	bullwhip	CDT_sub	-0.2710**	0.1190	0.023	4,556	Industry FE + Year FE
R4 Supplier FE	bullwhip	CDT	-0.3564**	0.1442	0.013	4,556	Supplier FE + Year FE
R5 Alternative DV	AR_supply	CDT	-0.0621	0.0631	0.325	4,556	Industry FE + Year FE

Note. All models include control variables. Standard errors are clustered at the supplier-firm level. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

Heterogeneity Analysis by External Uncertainty

Table 6 reports the heterogeneity analysis based on external uncertainty. The sample was divided into low- and high-uncertainty groups according to the median value of lnuncertainty. In the low-uncertainty group, the coefficient of CDT was -0.1917, with a clustered standard error of 0.1784 and a p-value of 0.282. The number of observations in this group was 2,317.

In the high-uncertainty group, the coefficient of CDT was -0.4078, with a clustered standard error of 0.1651 and a p-value of 0.014. The number of observations in this group was 2,239. Both models included control variables, industry fixed effects, and year fixed effects. These results indicate cross-subsample variation in the association rather than direct evidence of a measured mechanism. The complete heterogeneity results are presented in Table 6.

Table 6. Heterogeneity Analysis by External Uncertainty

Heterogeneity variable	Group	Coefficient of CDT	Clustered SE	p-value	N	Fixed effects	Controls
External uncertainty	Low uncertainty	-0.1917	0.1784	0.282	2,317	Industry FE + Year FE	Yes
External uncertainty	High uncertainty	-0.4078**	0.1651	0.014	2,239	Industry FE + Year FE	Yes

Note. The sample is divided by the median value of lnuncertainty. Standard errors are clustered at the supplier-firm level. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

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Discussion

Interpretation of the Empirical Findings

The empirical results revealed two main findings. Customer digital transformation was negatively and statistically significantly associated with the bullwhip effect in supplier–customer relationships among Chinese listed companies, and this association remained statistically significant across the logged dependent-variable specification, the alternative digital transformation indicator, and the supplier fixed-effects specification. The heterogeneity results further showed that the negative association was statistically significant in the high-uncertainty subsample but not in the low-uncertainty subsample.

These findings appear to indicate that customer-side digitalisation is relevant not only to the customer firm itself but also to the information environment faced by upstream suppliers. Because the bullwhip effect was used as a reverse proxy for supply chain information efficiency, the negative coefficient on customer digital transformation may suggest that digitally transformed customer firms are associated with lower demand information distortion in supplier–customer relationships. This interpretation should remain cautious, as the empirical design identifies associations rather than definitive causal effects.

The results support and extend the emerging literature on digital transformation spillovers in supply chains. Prior studies have shown that digital transformation may travel across vertical partnerships and shape supplier innovation, collaboration, audit risk, growth, and other inter-firm outcomes (Yang et al., 2022; Geng et al., 2024; L. Li et al., 2024; B. Li et al., 2024). The present findings extend this line of research by focusing on a relationship-level information outcome rather than a broad firm-level performance consequence. In this respect, the study positions customer-side digitalisation as a downstream information condition that may be associated with lower demand information distortion in supplier–customer relationships.

The findings also complement recent research on digitalisation and the bullwhip effect. Liu et al. (2025) reported that digital transformation was associated with lower firm-level bullwhip effects, while Sun et al. (2025) provided additional evidence that digital transformation may alleviate bullwhip-effect distortion in supply chains. Huang et al. (2026) further connected customer digital transformation with supplier-side risk-taking behaviour through the bullwhip-effect channel. Compared with these recent studies, the present paper adopts a narrower information-efficiency interpretation. It does not treat digital transformation merely as a general performance-enhancing capability, nor does it claim that digital transformation is the dominant determinant of the bullwhip effect. Instead, it examines whether customer-side digitalisation is associated with lower relationship-level demand information distortion in supplier–customer relationships. This positioning helps connect the digital transformation literature with supply chain information-efficiency research while avoiding an overstated causal or performance-based interpretation.

The statistically weaker result obtained when upstream supply-demand deviation was used as an alternative dependent variable qualifies the interpretation of the findings. The coefficient remained negative, but it was not statistically significant in this specification. This pattern suggests that the empirical association was clearer when the bullwhip effect was used as the outcome than when the broader upstream supply-demand deviation measure was used.

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Accordingly, the discussion of the findings should be centred on the bullwhip-effect measure as the main proxy for supply chain information efficiency, while acknowledging that the evidence was not uniformly strong across all alternative outcome specifications.

The relatively modest explanatory power of the regression models should also be interpreted cautiously. This is not unexpected because the bullwhip effect is shaped by multiple operational, relational, product-market, inventory-management, and macro-environmental factors that cannot be fully captured by a single customer-side digitalisation indicator. The empirical contribution is therefore not that customer digital transformation explains most variation in the bullwhip effect, but that it remains negatively associated with the main information-distortion proxy after fixed effects, controls, and several sensitivity checks are considered.

The findings should also be interpreted in relation to the paper's research positioning. The study is not designed to claim that customer digital transformation is the only or dominant determinant of supply chain information efficiency. Supplier capabilities, product characteristics, customer concentration, contractual arrangements, inventory policies, and market uncertainty may also shape the degree of demand amplification. The contribution lies in isolating customer-side digitalisation as a theoretically meaningful information condition and examining its association with a relationship-level indicator of information distortion. This more bounded positioning helps avoid overclaiming while still showing why customer digital capability matters for upstream coordination.

The results also reinforce the value of studying supply chain digitalisation at the relationship level. Firm-level digital transformation indicators can be informative, but supply chain outcomes often emerge from interdependence rather than from isolated organisational capability. A digitally transformed customer may influence the informational environment of its supplier even when the supplier's own digital capability is not the primary focus of analysis. This distinction matters for supply chain management research because it draws attention to the relational consequences of digital capability. It also suggests that digital transformation should be evaluated not only through internal efficiency, innovation, or financial outcomes, but also through its ability to improve the quality of information exchanged across organisational boundaries.

Theoretical Implications

The study offers several theoretical implications for supply chain management and digital transformation research. It extends the digital transformation literature by shifting the analytical focus from firm-internal outcomes to inter-firm information consequences. Much of the existing literature has examined productivity, innovation, financial performance, and capital-market responses. By contrast, the present study suggests that customer-side digitalisation may be linked to supply-chain-level information spillovers, particularly in the transmission of demand-related information between customers and suppliers.

The study also contributes to bullwhip-effect research by positioning the bullwhip effect as an observable reverse proxy for supply chain information efficiency. Prior bullwhip-effect studies have often treated the phenomenon as an operational fluctuation or inventory-management problem. The present study extends this view by treating the bullwhip effect as a measurable

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expression of information distortion in supplier–customer relationships. This approach provides a more focused empirical bridge between digital transformation and supply chain information efficiency.

The heterogeneity results further enrich the information-friction perspective. The stronger negative association observed under high external uncertainty may suggest that customer digital transformation becomes more relevant when suppliers face greater difficulty in interpreting and verifying demand-related signals. This finding supports the view that the value of digitalisation in supply chains is contingent on the information environment. Rather than assuming that digital transformation has uniform implications across all contexts, the results indicate that its information-related relevance may be more pronounced when uncertainty is higher.

Practical Implications

For policymakers, platform operators, and supply chain ecosystem designers, the findings suggest that digital infrastructure should be evaluated by its ability to reduce inter-firm information friction, not only by its ability to increase transaction volume. Policies and platform rules that support interoperable data standards, secure information sharing, reliable digital disclosure, order traceability, and auditable transaction records may improve supply chain information efficiency. Such initiatives are especially important for smaller suppliers that lack bargaining power and depend heavily on the quality of information provided by large or digitally advanced customers.

The findings are particularly relevant under high external uncertainty. In uncertain environments, historical demand patterns and informal relational knowledge become less reliable, while the value of timely and verifiable customer-side information increases. Managers should therefore prioritise digital information links with strategically important customers, especially in industries or periods characterised by demand volatility, supply disruption, policy change, or logistics instability. Under such conditions, supplier access to accurate customer-side information may help reduce excessive production adjustment and unnecessary inventory buffering.

For supply chain relationship managers, the practical value of digitalisation lies in converting digital records into usable coordination routines. Customer and supplier firms may benefit from agreed data-sharing procedures, standard definitions of order changes, clear responsibilities for updating fulfilment status, and escalation routines for demand shocks, logistics exceptions, and settlement disputes. These routines can reduce ambiguity when suppliers interpret downstream signals and can prevent operational responses based on incomplete or outdated information.

For supplier firms, the results suggest that customer digital capability can be used as a relationship-level information-quality signal. Suppliers that depend on customer-side demand information should not evaluate customers only by order volume, bargaining power, or payment terms. They may also need to assess whether key customers have reliable digital records, transparent demand revision procedures, accessible order histories, and verifiable transaction trails. This assessment can be incorporated into customer risk screening, production-planning routines, inventory-buffer decisions, and relationship-governance processes.

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The findings translate into several actionable implications for supply chain managers. Customer firms should treat digital transformation not only as an internal efficiency project but also as an information-governance capability that affects upstream coordination. Investments in digital systems are likely to be more valuable when they improve the visibility, traceability, and credibility of demand-related information. Relevant practices include maintaining traceable order and demand-change records, updating fulfilment and inventory status in a timely manner, preserving verifiable transaction and settlement histories, and providing suppliers with consistent information on delivery requirements, return flows, and operational adjustments.

Limitations and Future Research

Several limitations should be acknowledged. The sample was restricted to supplier–customer relationships among Chinese listed companies, which limits the generalisability of the findings to private firms, unlisted firms, small and medium-sized enterprises, and other institutional environments. Future research could examine whether similar associations hold in broader samples and cross-country supply chain settings.

The empirical design relied on ordinary least squares regressions with fixed effects. Although robustness checks were conducted, potential endogeneity may remain because unobserved relationship characteristics, reverse causality, or omitted supply chain conditions may still affect the estimates. The results should therefore be interpreted as empirical associations rather than definitive causal effects. Future studies could use stronger identification strategies, such as exogenous digital-policy shocks, staggered digital-transformation events, quasi-experimental designs, natural experiments, or matched supplier–customer panel designs, to examine causal relationships more directly.

The information-friction interpretation was developed theoretically but was not tested through directly measured search-cost or verification-cost variables. Future research could incorporate direct measures of information search, verification difficulty, data transparency, and inter-firm information quality. Such evidence would allow researchers to examine more precisely how digital transformation is linked to the reduction of information distortion across supply chain relationships.

The robustness test using AR_supply as an alternative dependent variable was statistically weaker. This limitation indicates that the evidence is stronger for the bullwhip effect as a relationship-level information-distortion measure than for a broader upstream supply-demand deviation outcome. Future research could compare multiple operationalisations of supply chain information efficiency, including forecast accuracy, order variability, inventory adjustment, information-sharing quality, and demand-planning responsiveness. This would help clarify the conditions under which customer digital transformation is most strongly associated with information-efficiency outcomes.

Concluding Remarks

This study examined whether customer digital transformation is associated with supply chain information efficiency in supplier–customer relationships among Chinese listed companies. Using 4,556 supplier–customer-year observations and treating the bullwhip effect as an observable reverse proxy for demand information distortion, the results show that customer

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digital transformation is negatively associated with the bullwhip effect. The main association remains supported in the logged dependent-variable specification, the alternative digital transformation measure, and the supplier fixed-effects specification, although the alternative outcome based on upstream supply-demand deviation provides weaker evidence.

The study contributes by reframing customer-side digital transformation as a downstream information-governance condition rather than only as a firm-level technological capability. By positioning the bullwhip effect as a relationship-level indicator of information inefficiency, the paper links digital transformation, information friction, and supply chain information efficiency within one focused empirical framework. The stronger association observed under high external uncertainty further suggests that the information value of customer digitalisation becomes more salient when suppliers face greater difficulty in interpreting and verifying demand-related signals.

The findings should be interpreted within the boundaries of the research design. The sample is limited to supplier–customer relationships among Chinese listed companies, the empirical estimates identify conditional associations rather than definitive causal effects, and information search cost and verification cost are theorised rather than directly measured. Future research could extend this study by using broader supplier–customer datasets, stronger identification strategies, direct measures of information friction, and alternative operational indicators of supply chain information efficiency.

Ethical Considerations and Data Statement

This study uses secondary archival data collected from publicly available listed-company disclosures and open secondary data resources covering Chinese listed firms and supplier–customer relationships. The study does not involve direct interaction with human participants, survey respondents, interviews, experiments, interventions, or private personal records. Because the analysis relies on publicly available firm-level and relationship-level archival data rather than human-subject data collection, formal human-subjects ethics approval was not required for the secondary-data analytical procedures reported in this paper. The authors nevertheless followed standard research integrity principles by using the data only for academic purposes, reporting results in aggregate form, and avoiding any attempt to identify individuals.

The empirical data were assembled from public listed-company disclosures and public secondary data resources, including the Pipixia Database organized and managed by the Pipixia Team. Access to the original data is subject to the relevant data provider's terms of use. The cleaned analytical dataset and coding information may be made available by the corresponding author upon reasonable request where permitted by applicable data-use restrictions.

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