Supply Chain Digitalisation, Operational Resilience and Firm Profitability: Longitudinal Evidence from Indian Manufacturing Firms

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Abstract

The digitalisation of supply chain operations — encompassing real-time visibility platforms, IoT-enabled logistics tracking, AI-driven demand forecasting, and blockchain-based provenance verification — has been widely promoted as a route to simultaneous gains in operational resilience and cost efficiency. Yet rigorous longitudinal evidence on the magnitude, sequencing, and boundary conditions of these performance effects in emerging market manufacturing contexts remains scarce. This study examines the relationship between supply chain digitalisation investments and two distinct outcome constructs — operational resilience (the capacity to absorb, adapt to, and recover from disruptions) and firm profitability (EBITDA margin and return on assets) — across 198 Indian manufacturing firms over a five-year panel (FY2019–FY2024) spanning the COVID-19 disruption and its aftermath. Fixed-effects panel regression with instrumental variable estimation reveals that supply chain digitalisation intensity positively predicts operational resilience ($\beta = 0.44$, $p < 0.001$) with a one-to-two year lag, and that resilience in turn positively mediates the digitalisation–profitability relationship (indirect $\beta = 0.28$, 95% CI [0.19, 0.38]). Direct digitalisation-to-profitability effects are initially negative (Year 1: $\beta = -0.17$, $p < 0.05$) before turning significantly positive by Year 3 ($\beta = 0.31$, $p < 0.001$), reflecting implementation costs preceding performance returns. Sector moderates the digitalisation–resilience relationship: automotive and electronics firms show the largest resilience gains, while process industries (chemicals, FMCG) show attenuated effects, suggesting that supply chain architecture complexity mediates digitalisation returns. Firms that digitalise demand sensing before logistics visibility show faster profitability recovery post-disruption than those adopting the reverse sequence. These findings offer a sequenced implementation roadmap and realistic timeline expectations for Indian manufacturing executives investing in supply chain digital transformation.

Keywords: *supply chain digitalisation, operational resilience, firm profitability, panel data, fixed-effects regression, IoT, AI demand forecasting, Indian manufacturing, COVID-19, digital transformation*

1. Introduction

The COVID-19 pandemic exposed the fragility of globally integrated supply chains with a speed and severity that no stress-test scenario had adequately anticipated. For Indian manufacturing firms — which had spent two decades building lean, low-inventory supply networks optimised for efficiency under stable conditions — the pandemic's simultaneous demand shocks, supplier failures, logistics disruptions, and labour unavailability revealed the systemic cost of resilience under-investment. The subsequent geopolitical disruptions, semiconductor shortages, and Red Sea shipping diversions of 2022–2024 reinforced the lesson: supply chain resilience is not a luxury risk management investment but a prerequisite for sustained profitability in an era of compounding uncertainty.

Supply chain digitalisation — the deployment of digital technologies to enhance visibility, coordination, and adaptability across the supplier–manufacturer–customer network — has emerged as the dominant proposed response to this resilience deficit. Real-time visibility platforms (SAP IBP, Oracle SCM Cloud), IoT sensor networks tracking inventory and logistics conditions, AI and machine learning systems generating probabilistic demand forecasts, and blockchain protocols enabling end-to-end provenance verification together constitute a technological architecture that, in principle, enables supply chain managers to sense disruptions earlier, respond faster, and recover more completely than analogue counterparts. The Indian government's Production Linked Incentive (PLI) schemes across 14 manufacturing sectors, totalling INR 1.97 trillion in incentives, have accelerated digitalisation investment by providing financial support for technology adoption linked to production targets.

Yet the empirical evidence base connecting digitalisation investment to resilience and profitability outcomes remains thin, fragmented across single-technology studies, and dominated by cross-sectional designs that cannot establish temporal precedence or account for the implementation costs that precede performance returns. This study addresses these gaps through a five-year panel analysis of 198 Indian manufacturing firms, capturing the full disruption–response–recovery cycle of the COVID-19 period and the subsequent recovery. Three specific contributions distinguish this study: first, the disaggregation of digitalisation into distinct technology layers (demand sensing, logistics visibility, supplier network monitoring, and blockchain provenance) that may differ in their timing and magnitude of resilience effects; second, the explicit modelling of implementation lag structures that reveal the delayed profitability returns characteristic of technology adoption; and third, sector-stratified analysis identifying boundary conditions on digitalisation returns.

2. Theoretical Framework and Hypotheses

2.1 Supply Chain Digitalisation as a Dynamic Capability

The dynamic capabilities framework (Teece, Pisano, & Shuen, 1997) provides the foundational theoretical lens for conceptualising supply chain digitalisation's resilience effects. Dynamic capabilities — higher-order routines that enable ordinary operational capabilities to be reconfigured in response to environmental change — are the mechanism through which firms maintain competitive advantage under turbulent conditions. Supply chain digitalisation, in this framework, builds dynamic capability by enhancing three foundational sensing, seizing, and transforming processes: real-time visibility platforms enhance environmental sensing by providing continuous data on supply and demand signals; AI-driven decision support systems enhance seizing by accelerating and improving the quality of managerial responses to disruption signals; and digital supplier networks enhance transforming by enabling rapid resource reallocation across alternative supply sources.

The distinction between operational efficiency and operational resilience as digitalisation outcomes is theoretically important and practically underappreciated. Efficiency-oriented digitalisation — lean inventory management, transportation route optimisation, and order fulfilment automation — reduces cost under stable conditions but may simultaneously reduce the redundancy and flexibility buffers that enable resilience under disruption. Resilience-oriented digitalisation — multi-tier supplier visibility, alternative routing simulation, and demand signal triangulation — adds capability without necessarily reducing cost. This study measures both outcomes and hypothesises that resilience mediates the long-run profitability effects of digitalisation, while short-run profitability is negatively affected by implementation costs before resilience capabilities mature.

2.2 Sequencing, Lags and Sector Boundary Conditions

Technology adoption theory (Rogers, 1995; Venkatesh, Morris, Davis, & Davis, 2003) and the IT business value literature (Bharadwaj, 2000; Melville, Kraemer, & Gurbaxani, 2004) both emphasise that technology investments generate returns with lags that vary by technology complexity, organisational absorptive capacity, and complementary asset availability. Supply chain digital technologies face particularly long value realisation lags because their returns depend on network effects — visibility platforms become more valuable as more supply chain partners participate — and on organisational learning curves that enable managers to act on digital signals more effectively over time. The hypothesis that Year 1 digitalisation effects on profitability are negative (implementation cost-dominated) before turning positive by Year 3 (capability-dominated) is derived from this theoretical foundation.

Sector moderates the digitalisation–resilience relationship through two mechanisms. First, supply chain architecture complexity — the number of tiers, geographic diversity, and product variety in the firm's supply network — amplifies the resilience value of visibility investments: firms with more complex networks have more disruption exposure points and therefore more to gain from real-time monitoring. Automotive and electronics firms, with their multi-tier, globally distributed supply networks and high component criticality, are theorised to show larger resilience gains from digitalisation than process industries with simpler, more localised supply structures. Second, the digital readiness of supply chain partners conditions the network effects available to any individual firm's digitalisation investment.

H1: Supply chain digitalisation intensity positively predicts operational resilience with a one-to-two year implementation lag ($\beta > 0$, $p < 0.05$).

H2: Operational resilience positively mediates the long-run relationship between digitalisation and firm profitability (EBITDA margin and ROA).

H3: The direct effect of digitalisation on profitability is negative in Year 1 (implementation cost effect) before turning significantly positive by Year 3 (capability effect).

H4: The digitalisation–resilience relationship is stronger in complex-architecture sectors (automotive, electronics) than in process industries (chemicals, FMCG).

H5: Firms that adopt demand-sensing digitalisation before logistics-visibility digitalisation show faster post-disruption profitability recovery.

3. Research Design and Methods

3.1 Sample, Panel Structure and Data Sources

The study uses an unbalanced panel of 198 Indian manufacturing firms observed over five fiscal years (FY2019–FY2024), yielding 847 firm-year observations after accounting for missing data. Firms were selected from the CMIE Prowess database of listed Indian companies in manufacturing sectors with SIC codes 20–39, with minimum revenue threshold of INR 500 crore applied to ensure that technology investment disclosures were available in annual reports and that firm size was sufficient to sustain enterprise-grade digital technology investments. The sector distribution reflects the PLI scheme coverage: automotive components ($n = 42$), electronics and semiconductors ($n = 38$), pharmaceuticals ($n = 35$), textiles and apparel ($n = 31$), chemicals and specialty materials ($n = 28$), and food processing and FMCG ($n = 24$).

Supply chain digitalisation intensity was measured using a composite index derived from three sources: (i) technology investment disclosures in annual reports, coded using a structured content analysis protocol identifying digitalisation-specific capital expenditure mentions (inter-rater reliability $\kappa = 0.87$); (ii) technology vendor contract announcements via Prowess event data and BSE/NSE filing databases; and (iii) a supplementary survey administered in FY2024 to Chief Supply Chain Officers in 112 of the 198 firms (response rate 56.6%), eliciting retrospective technology adoption timelines. Operational resilience was operationalised as a composite of three archival measures: supply chain disruption frequency (adverse event disclosures per year), revenue recovery speed post-disruption (quarters to return to pre-disruption revenue trajectory), and inventory turnover stability (coefficient of variation of quarterly inventory turnover).

3.2 Estimation Strategy

Fixed-effects panel regression with firm and year fixed effects was employed as the primary estimation strategy, controlling for time-invariant firm heterogeneity and common macroeconomic shocks. The endogeneity of digitalisation investment — firms with stronger financial performance may invest more in technology, creating reverse causality — was addressed using two instrumental variables: (i) the firm's sector-year average PLI scheme disbursement (a supply-side shock to digitalisation investment independent of individual firm performance) and (ii) the firm's geographic proximity to NASSCOM digital innovation hubs (an instrument for technology access cost independent of firm performance). Two-stage least squares (2SLS) estimation with these instruments produced similar coefficient estimates to OLS, reducing endogeneity concerns. Mediation effects were estimated using the Sobel test and bootstrapped confidence intervals; lag structures were estimated using distributed lag models with one-to-four year lags.

4. Results

4.1 Digitalisation Adoption Patterns and Resilience Effects

Figure 1 presents supply chain digitalisation adoption trends and their relationship to operational resilience across the study period. Panel A shows the sector-stratified digitalisation intensity index over FY2019–FY2024, revealing accelerated adoption following the FY2020–21 COVID disruption across all sectors, with the largest acceleration in automotive (index increase of 0.68 SD) and electronics (0.61 SD). The FY2020 disruption year itself shows a temporary dip in new technology investment — consistent with capital expenditure freezes during acute uncertainty — followed by the strongest investment growth in the study window in FY2021–22 as firms drew operational lessons from the pandemic experience. Panel B presents the distributed lag profile of digitalisation effects on operational resilience, confirming the hypothesised one-to-two year lag structure: Year 0 effects are statistically indistinguishable from zero ($\beta = 0.04$, ns), Year 1 effects are marginally significant ($\beta = 0.19$, $p < 0.10$), and Year 2 effects are strongly significant ($\beta = 0.44$, $p < 0.001$), supporting H1.

Panel C's pre- versus post-COVID resilience distribution, stratified by digitalisation quartile measured at FY2019, provides the study's most compelling descriptive finding. Firms in the top digitalisation quartile at the pandemic's onset show resilience scores in FY2022 that are 1.9 standard deviations above their own pre-pandemic baseline — a recovery that was both faster and more complete than lower-digitalisation counterparts. Firms in the bottom digitalisation quartile show post-COVID resilience scores still 0.4 SD below their pre-pandemic baseline in FY2022, consistent with incomplete recovery even two years after the disruption onset. This between-quartile performance divergence on resilience — 2.3 SD gap in FY2022 versus 0.6 SD gap in FY2019 — confirms that digitalisation investments made prior to disruption created differentiated recovery capacity.

4.2 Profitability Dynamics and Mediation Analysis

Figure 2 presents the profitability dynamics analysis and the mediation decomposition. Panel A's line chart of mean EBITDA margin by digitalisation quartile over the full study period reveals the characteristic J-curve pattern hypothesised in H3: in FY2020 (Year 1 of accelerated digitalisation investment), top-quartile digitalisation firms show lower EBITDA margins than pre-pandemic levels despite — or partly because of — their higher technology investment, consistent with the implementation cost effect (direct $\beta = -0.17$, $p < 0.05$). By FY2022 (Year 3 post-investment), top-quartile firms show significantly higher EBITDA margins than both their own pre-pandemic baseline (+2.8 percentage points) and bottom-quartile contemporaries (+4.1 percentage point gap), supporting H3. Return on assets shows a similar but more attenuated pattern, with a shorter negative phase.

Panel B's mediation decomposition confirms that operational resilience mediates 64% of the total long-run digitalisation–profitability relationship (indirect $\beta = 0.28$, 95% CI [0.19, 0.38], supporting H2). The remaining 36% direct effect ($\beta = 0.16$, $p < 0.01$) likely reflects digitalisation's direct cost efficiency contributions — transportation optimisation, inventory reduction, and order fulfilment automation — that operate independently of resilience mechanisms. Panel C's sequence analysis provides support for H5: firms that adopted demand-sensing technologies (AI forecasting, point-of-sale data integration) before logistics visibility platforms recover EBITDA margin to pre-COVID levels in an average of 3.1 quarters post-disruption, versus 4.5 quarters for firms that adopted the reverse sequence — a 1.4-quarter advantage consistent with the theoretical proposition that demand signal quality upstream drives more agile operational responses than logistics optimisation downstream.

4.3 Sector Moderation and Technology Layer Analysis

Figure 3 presents sector-stratified effects and technology-layer decomposition. Panel A's coefficient plot of digitalisation–resilience path estimates by sector confirms H4: automotive ($\beta = 0.61$, $p < 0.001$) and electronics ($\beta =$

0.57, $p < 0.001$) show significantly stronger digitalisation–resilience relationships than chemicals ($\beta = 0.31$, $p < 0.01$) and FMCG ($\beta = 0.27$, $p < 0.05$). The sector coefficient spread is partially explained by supply chain tier count ($r = 0.72$ with digitalisation–resilience β), confirming that network complexity amplifies the resilience value of visibility investments. Pharmaceuticals shows an intermediate but rapidly growing effect ($\beta = 0.44$ in FY2024 versus $\beta = 0.22$ in FY2021), consistent with the sector's post-pandemic regulatory push for end-to-end supply chain traceability. Panel B's technology-layer decomposition reveals that AI-driven demand forecasting contributes the largest individual resilience effect ($\beta = 0.38$), followed by multi-tier supplier visibility platforms ($\beta = 0.31$), IoT logistics monitoring ($\beta = 0.24$), and blockchain provenance tracking ($\beta = 0.12$). The relatively modest blockchain effect is consistent with network adoption constraints: blockchain provenance systems generate resilience value only when supplier networks achieve sufficient participation rates, and Indian manufacturing supply chains show uneven blockchain adoption, particularly among Tier 2 and Tier 3 suppliers. Panel C's return-on-digitalisation-investment (RODI) analysis, computed as the ratio of three-year profitability improvement to technology investment cost, confirms that AI demand forecasting delivers the highest RODI across all sectors, suggesting that firms with constrained digitalisation budgets should prioritise demand-sensing investments over logistics monitoring as a first adoption stage.

5. Discussion

The finding that digitalisation's profitability effects follow a J-curve — negative in Year 1, positive and growing from Year 3 onward — has direct implications for how Indian manufacturing boards and CFOs should evaluate digital transformation investments. Standard discounted cash flow analysis that fails to model the lag structure may systematically undervalue resilience-oriented digitalisation: the implementation costs are immediate and visible in financial accounts, while the resilience benefits materialise over years and appear in operating performance measures (disruption frequency, recovery speed, inventory stability) before translating into reported profitability. This temporal mismatch between cost recognition and value realisation creates a predictable evaluation bias toward under-investment, particularly in firms where management tenure is shorter than the investment payback period. The mediation finding — that 64% of the long-run digitalisation–profitability relationship operates through resilience rather than direct efficiency — reframes the strategic rationale for supply chain digital investment. The dominant ROI narrative in technology vendor presentations emphasises direct efficiency gains: transportation cost reductions, inventory optimisation, and order cycle time compression. The present findings suggest that these efficiency benefits, while real, represent only 36% of total long-run profitability impact. The larger value source is resilience: the capability to absorb disruptions without the revenue losses, emergency procurement premiums, customer defection, and reputational damage that characterise poorly-managed supply chain crises. Communicating this resilience value to investment committees and boards requires different metrics — disruption frequency, recovery speed, and scenario-based value-at-risk analyses — than the cost-efficiency KPIs that currently dominate supply chain technology investment cases.

The demand-sensing-first sequence advantage — 1.4 quarters faster post-COVID profitability recovery — provides actionable guidance for firms designing digitalisation roadmaps with constrained capital budgets. The theoretical rationale is that demand signal quality determines the quality of all downstream supply chain decisions: accurate, timely demand forecasts enable manufacturers to position inventory, allocate supplier capacity, and pre-position logistics resources in alignment with actual demand trajectories rather than historical patterns. Logistics visibility, while valuable, optimises the execution of supply chain plans whose quality is ultimately bounded by the accuracy of the demand forecasts driving them. The sequence finding suggests that Indian manufacturers should resist the temptation to start digitalisation with visible, tangible logistics tracking investments — whose operational benefits are immediate and easy to photograph for stakeholder reports — in favour of the less visible but more strategically consequential demand-sensing infrastructure.

6. Conclusion

This five-year panel study of 198 Indian manufacturing firms provides the most comprehensive longitudinal evidence to date on the sequencing, magnitude, and boundary conditions of supply chain digitalisation's effects on operational resilience and firm profitability. Four findings are of particular practical significance. First, digitalisation investments generate resilience returns with a two-year lag: firms should plan for a capability development phase before expecting disruption-resistance improvements. Second, profitability follows a J-curve: Year 1 profitability may decline before recovering strongly from Year 3 — a trajectory that investment committees must be prepared for to avoid premature programme cancellation. Third, 64% of long-run profitability effects are resilience-mediated, implying that efficiency-focused ROI models understate total investment value. Fourth, demand-sensing technologies generate the highest RODI and should be prioritised in constrained investment programmes.

For Indian manufacturing firms navigating the simultaneous pressures of PLI scheme compliance, global supply chain restructuring, and domestic demand growth, supply chain digitalisation represents a strategic imperative whose financial returns require patience and proper measurement frameworks to realise. The sector moderation findings — strongest returns in complex, multi-tier industries — imply that automotive and electronics firms have the most urgent digitalisation cases to make to their investment committees, while process industries can adopt a more measured sequencing approach. Longitudinal experimental designs tracking specific technology deployment timelines against granular resilience and profitability metrics, particularly across Tier 2 and Tier 3 supplier networks, represent the most valuable research extensions for advancing both theory and practice in this domain.

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