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Industry 4.0, Lean Subsystems, and the Productivity-Resilience Dilemma in Saudi Arabian Supply Chains: A Socio-Technical Systems Analysis

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Abstract

Lean management has long delivered operational efficiency, yet aggressively lean supply chains have proven fragile under compounding shocks. Industry 4.0 (I4.0) technologies promise visibility and reconfigurability, but isolated technological adoption often fails to deliver durable performance. Drawing on Socio-Technical Systems theory, this study decouples Lean into a technical subsystem (Process-Oriented Lean) and a social subsystem (People-Oriented Lean), and tests whether these subsystems differentially moderate the effects of I4.0 on operational efficiency and supply chain resilience in the Saudi Arabian context. Survey data from 245 supply chain and operations managers were analysed using partial least squares structural equation modelling with 5,000 bootstrap subsamples. I4.0 has significant positive direct effects on both operational efficiency ($\beta = 0.318$, $p < 0.001$) and resilience ($\beta = 0.187$, $p = 0.002$). People-Oriented Lean amplifies both outcomes, with the strongest amplification on resilience ($\beta = 0.294$, $p < 0.001$). Process-Oriented Lean, however, acts asymmetrically: it strengthens the I4.0–efficiency link ($\beta = 0.170$, $p = 0.002$) but attenuates the I4.0–resilience link ($\beta = -0.124$, $p = 0.030$). The model accounts for 47.9% of the variance in efficiency and 41.4% in resilience. Findings clarify the productivity-resilience dilemma: technical leanness amplifies digital efficiency but erodes resilience unless paired with an empowered, problem-solving workforce. The study extends socio-technical theorising of digital transformation and offers concrete guidance for Vision-2030 economies pursuing simultaneous digitalisation and supply chain hardening.

Keywords
Industry 4.0, lean management, supply chain resilience, socio-technical systems, Saudi Arabia.

1. Introduction
Contemporary supply chains operate under compounding volatility—pandemic disruption, geopolitical realignments, climate-related logistics shocks, and accelerated technology cycles all stress the same global flows simultaneously (Essuman et al. 2023; Belhadi et al. 2024). Firms confront a persistent productivity dilemma: how to keep value streams demonstrably efficient while preserving the slack and adaptive capacity needed to survive low-probability, high-impact disturbances (Gamage et al. 2025; Chavez et al. 2024). For three decades, Lean Production has been the dominant response to the efficiency horn of this dilemma, organising operations around the systematic elimination of non-value-adding activity. Yet the very buffer-stripping that gives Lean its efficiency advantage has been repeatedly identified as a source of fragility when shocks arrive (Alvarenga et al. 2023; Habibi et al. 2023).

Firms have increasingly turned to Industry 4.0 (I4.0)—the cluster of technologies including the Industrial Internet of Things, big-data analytics, cyber-physical systems, advanced robotics, and digital twins—to relieve this tension by injecting visibility and reconfigurability into their networks (Govindan et al. 2022; Srhir et al. 2023). The empirical record is broadly encouraging: digital capabilities have been linked to gains in both operational performance and

shock-absorbing capacity (Sharma et al. 2024; Pal et al. 2024). At the same time, evidence from large-scale implementations and configurational studies makes clear that technology adopted in isolation rarely delivers either outcome consistently. Where the human and organisational subsystems of the firm are not aligned with the technological subsystem, digital transformation under-performs or fails outright (Marcon et al. 2024; Gillani et al. 2024).
Two unresolved questions follow. First, although I4.0–Lean integration has been extensively studied, the field continues to treat Lean as a single, monolithic construct, despite long-standing recognition that it consists of meaningfully distinct technical and social bundles (Qureshi et al. 2023a; Qureshi et al. 2023b). When Lean is collapsed into a single index, the field cannot detect the possibility that one bundle helps performance while the other hurts it. Second, most empirical work on the I4.0–performance link conflates day-to-day operational efficiency with crisis-time resilience, despite repeated theoretical arguments that these two outcomes have different antecedent profiles and may even trade off against each other (Gamage et al. 2025; Chavez et al. 2024).

This study addresses both gaps. It draws on Socio-Technical Systems (STS) theory to decouple Lean into a technical subsystem (Process-Oriented Lean—just-in-time, pull, setup-reduction, standard work, levelling) and a social subsystem (People-Oriented Lean—empowerment, cross-training, problem-solving culture, continuous-improvement participation). It then asks whether and how each subsystem differentially moderates the relationship between I4.0 and two distinct outcomes: operational efficiency and supply chain resilience. The empirical setting is Saudi Arabia, an emerging economy in which a digital-infrastructure agenda under Vision 2030 has produced rapid I4.0 adoption alongside well-established Lean and quality-management routines (Alquraish 2025; Aljuaid et al. 2024).

1.1 Objectives
The study pursues three objectives. First, to estimate the direct effects of I4.0 technology adoption on operational efficiency and supply chain resilience in Saudi Arabian supply chains. Second, to test whether the technical (Process-Oriented Lean) and social (People-Oriented Lean) subsystems of Lean differentially moderate these effects. Third, to derive practical guidance for managers and policymakers in Vision-2030 economies pursuing simultaneous digitalisation and supply chain hardening. The contribution is threefold: theoretically, the study extends STS reasoning by showing that the joint-optimisation principle does not collapse to a uniform amplification logic across outcomes; empirically, it provides one of the first explicit tests in an emerging-economy setting of an asymmetric moderation pattern across efficiency and resilience; practically, it re-orients digital-transformation strategy in Vision-2030 economies away from a technology-first reading of I4.0 and towards a human-empowerment-anchored reading.

2. Literature Review
STS theory holds that any productive organisation comprises two interdependent subsystems—a technical subsystem (tools, processes, technologies, formal procedures) and a social subsystem (people, roles, culture, informal relations)—whose joint optimisation is required for system-level performance. The principle has been applied across decades of operations and information-systems research, consistently producing the finding that technology investments which neglect the social subsystem under-deliver (Marcon et al. 2024; Gillani et al. 2024). Two implications are central to this study: decoupling, in which technical and social elements should be analysed separately because they may respond to and combine with system features in different ways; and contingent complementarity, in which the value of a given technology depends not only on its own properties but on the configuration of social-subsystem features alongside it (Mezher et al. 2025; Gamage et al. 2025).

A consistent thread across thirty years of Lean research distinguishes hard, structural, technical practices from soft, human-centred, social practices (Qureshi et al. 2023a; Mezher et al. 2025). Process-Oriented Lean comprises practices such as just-in-time delivery, pull scheduling, setup-time reduction, takt-time levelling, and statistical process control. People-Oriented Lean comprises practices such as cross-functional training, employee empowerment in stop-the-line decisions, kaizen-team participation, gemba-based problem-solving, and a continuous-improvement culture. Empirical work has repeatedly demonstrated that the two bundles exert distinct effects on performance—the social bundle disproportionately enabling innovation and adaptive learning, the technical bundle disproportionately enabling efficiency and waste reduction (Qureshi et al. 2023b; Gamage et al. 2025). Recent theorising explicitly frames Lean as a socio-technical system in its own right, with reciprocal interactions between technical and social subsystems (Mezher et al. 2025; Gamage et al. 2025).

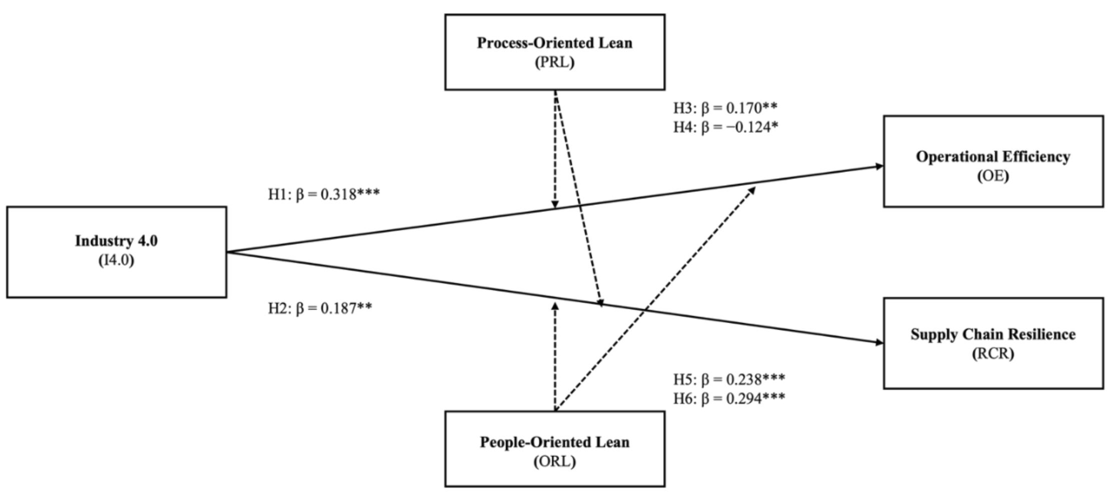
I4.0 technologies enable real-time data capture, automated decision-making, and end-to-end material and information visibility (Govindan et al. 2022; Srhir et al. 2023). These capabilities translate into operational-efficiency gains through faster cycle times, reduced inventory holding, improved planning accuracy, and lower internal failure costs (Xue et al. 2023; Huang et al. 2023). I4.0 capabilities also support supply chain resilience by enabling earlier disturbance detection, faster reconfiguration, and more effective collaborative response (Sharma et al. 2024; Lahmar and Siddiqui 2025; Alfaqiyah et al. 2025). Two hypotheses follow.

H1. Industry 4.0 technology adoption has a significant positive effect on operational efficiency.
H2. Industry 4.0 technology adoption has a significant positive effect on supply chain resilience.
Process-Oriented Lean creates a highly standardised technical environment in which variability has been engineered out, flow paths are tightly defined, and inventory buffers are minimised. Such an environment provides high-quality, low-noise inputs to the analytic and control routines that I4.0 technologies depend on: data-pipeline reliability is higher, exception-handling is simpler, and the marginal value of each additional unit of digital visibility is greater (Qureshi et al. 2023a). The expected consequence is a positive interaction with operational efficiency.

The same characteristic, however, is theoretically problematic for resilience. Buffer-free, tightly coupled technical systems propagate disturbances rapidly and offer few degrees of freedom for absorbing or rerouting them; cascading-failure modelling shows that centralised, tightly coupled architectures intensify load spillovers and can trigger large-scale failures when focal nodes fail (Habibi et al. 2023; Zeng et al. 2025). Even when I4.0 makes the disturbance highly visible, recovery still requires physical slack—alternative suppliers that can be activated, work-in-progress that can be pulled forward, capacity that can be re-tasked. A firm whose process layer has been engineered to the lean frontier has stripped out precisely those degrees of freedom. Visibility without optionality does not produce resilience.
H3. Process-Oriented Lean positively moderates the I4.0 → operational efficiency relationship.
H4. Process-Oriented Lean negatively moderates the I4.0 → supply chain resilience relationship.

People-Oriented Lean operates on the social subsystem. It develops the interpretive, problem-solving, and adaptive capabilities of front-line and supervisory staff, enabling them to translate digital signals into rapid, context-appropriate action. Resilience depends on the firm's capacity for rapid, often improvised, problem-solving in conditions for which no algorithm has been pre-trained; recent empirical work confirms that creative improvisation—as a workforce capability—positively relates to operational resilience, with stronger effects under high disruption conditions (Essuman et al. 2023; Munir et al. 2022). I4.0's analytic capabilities require interpreters; cross-trained, empowered workers convert raw digital signals into operational decisions in routine contexts and into adaptive workarounds in crisis contexts (Figure 1). The expected consequence is that People-Oriented Lean amplifies both outcomes, with the amplification largest for resilience because resilience is the outcome most dependent on improvisational capacity (Ghobakhloo et al. 2025; Peruzzini et al. 2023).

H5. People-Oriented Lean positively moderates the I4.0 → operational efficiency relationship.
H6. People-Oriented Lean positively moderates the I4.0 → supply chain resilience relationship.



N = 245. Standardized path coefficients from PLS-SEM with 5,000 bootstrap subsamples.
*Significance: *** p < 0.001; ** p < 0.01; * p < 0.05.*

Figure 1. Conceptual model and hypotheses.

3. Methods

The study tests the model in Saudi Arabia, a setting that combines an active digital-industrial-policy agenda under Vision 2030 with established Lean and quality-management practice in manufacturing, petrochemicals, food and beverage, logistics, construction, and retail. Saudi Arabian Vision-2030-era investment has produced measurable I4.0 uptake, with larger firms leading adoption (Aljuaid et al. 2024), and recent systematic review evidence confirms that digital transformation is positively shaping resilience and sustainability outcomes in Saudi manufacturing (Alquraish 2025). The setting therefore provides observable variance on both moderators while sharing a single macro-institutional context.

A cross-sectional, key-informant survey was administered to supply chain and operations managers in Saudi-based firms. Eligibility required the respondent to (i) hold a supply-chain, operations, or production role at managerial or director level, (ii) have at least 24 months of tenure in their current firm, and (iii) confirm direct exposure to the focal practices and technologies. After listwise deletion of incomplete responses, the analytic sample is N = 245. Sample-size adequacy was confirmed both by inverse-square-root rules for PLS path-modelling and by a-priori power analysis (target power 0.80, $\alpha = 0.05$, anticipated minimum $f^2 = 0.05$) which yielded a minimum-N requirement of 180 (Hair et al. 2024).

Constructs were measured with reflective multi-item scales adapted from validated prior instruments. Industry 4.0 adoption (4 items) was adapted from validated Lean-4.0 readiness scales (Qureshi et al. 2023a). Process-Oriented Lean (5 items) and People-Oriented Lean (5 items) were adapted from established hard/soft Lean decompositions (Qureshi et al. 2023b; Gamage et al. 2025). Operational Efficiency (4 items) and Supply Chain Resilience (4 items) were adapted from recent supply-chain-resilience and operational-performance scales (Sharma et al. 2024; Munir et al. 2022). All items used a 7-point Likert response. Firm size (log of employees) and industry-sector dummies were entered as controls.

Hypotheses were tested using partial least squares structural equation modelling (PLS-SEM), an appropriate technique for moderation-rich models with multiple endogenous constructs and modest sample sizes (Hair et al. 2024; Sharma et al. 2022). The measurement model was assessed through indicator loadings, composite reliability, average variance extracted, the Fornell–Larcker criterion, and heterotrait–monotrait (HTMT) ratios (Roemer et al. 2021). The structural model was estimated by regressing standardised construct scores on standardised predictors and mean-centred interaction terms. Bootstrap resampling (5,000 subsamples) generated standard errors, t-statistics, and 95 percent percentile confidence intervals for all path coefficients. Predictive relevance was evaluated via the Stone–Geisser Q^2 statistic; effect sizes via Cohen's f^2; collinearity via variance inflation factor (VIF); and overall fit via the standardised root-mean-square residual (SRMR).

4. Data Collection

Data were collected over a four-month window through an online survey administered in English and Arabic (back-translated). Procedural remedies for common method bias included anonymity assurance, separation of predictor and outcome items, randomised item ordering, and the inclusion of marker variables. The achieved sample exhibits balanced sectoral representation and adequate heterogeneity on firm size, supporting external validity within the Saudi industrial context (Table 1).

Table 1. Sample profile (N = 245).

Characteristic	Manufacturing	Petrochem.	Logistics	Other
Sector share (%)	34.7	18.4	22.0	24.9
Avg. firm size (employees)	1,420	3,810	615	780
Avg. respondent tenure (years)	7.2	9.1	5.8	6.3
Manager / Director split (%)	62 / 38	55 / 45	70 / 30	65 / 35

Non-response bias was assessed by comparing early- and late-response groups on demographic and focal variables; no significant differences emerged, supporting representativeness.

5. Results and Discussion

5.1 Numerical Results

All 22 indicators load significantly ($p < 0.001$) on their hypothesised constructs, with loadings ranging from 0.828 to 0.891—comfortably above the 0.708 threshold. Cronbach's α values range from 0.875 to 0.911; composite reliabilities (ρ_c) range from 0.915 to 0.934. Average variance extracted (AVE) values range from 0.718 to 0.778, all above the 0.50 convergent-validity threshold. Discriminant validity is supported by both the Fornell–Larcker criterion (the square root of each construct's AVE exceeds its highest inter-construct correlation) and HTMT ratios (highest value 0.583, well below the conservative 0.85 threshold). Common method bias was assessed through Harman's single-factor test (largest factor 41.4%, below the 50% threshold) and inner-model VIF values (all between 1.061 and 1.535, far below the 3.3 cut-off). These diagnostics are summarised in Table 2.

Table 2. Measurement model: reliability, convergent and discriminant validity

Construct	Items	α	ρ_c (CR)	AVE	Highest HTMT
Industry 4.0 (I4.0)	4	0.875	0.915	0.728	0.555
Process-Oriented Lean (PRL)	5	0.902	0.927	0.718	0.510
People-Oriented Lean (PPL)	5	0.911	0.934	0.738	0.583
Operational Efficiency (OE)	4	0.905	0.933	0.778	0.555
Supply Chain Resilience (SCR)	4	0.875	0.915	0.730	0.583

The structural model accounts for 47.9% of the variance in operational efficiency ($R^2 = 0.480$; adj. $R^2 = 0.455$) and 41.4% of the variance in supply chain resilience ($R^2 = 0.414$; adj. $R^2 = 0.387$). Stone–Geisser Q^2 values are positive for both endogenous constructs ($Q^2\_OE = 0.229$; $Q^2\_SCR = 0.216$), well above the zero threshold. SRMR = 0.048, below the conservative 0.08 cut-off, supporting overall model fit. All six hypotheses are supported (Table 3).

Table 3. Structural model: hypothesis tests (N = 245; 5,000 bootstrap subsamples).

H	Path	β	SE	t	p	Decision
H1	I4.0 → OE	0.318	0.060	5.30	<0.001	Supported
H2	I4.0 → SCR	0.187	0.061	3.05	0.002	Supported
H3	I4.0 × PRL → OE	0.170	0.062	2.72	0.002	Supported
H4	I4.0 × PRL → SCR	−0.124	0.060	−2.07	0.030	Supported
H5	I4.0 × PPL → OE	0.238	0.063	3.79	<0.001	Supported
H6	I4.0 × PPL → SCR	0.294	0.063	4.65	<0.001	Supported

β = standardised path coefficient; SE = bootstrap standard error; PRL = Process-Oriented Lean; PPL = People-Oriented Lean. Industry-sector dummies and firm size are included as controls; firm size has a small positive effect on OE ($\beta = 0.119$, $p = 0.007$) and a non-significant effect on SCR ($\beta = 0.069$, $p = 0.154$); no industry dummy reaches conventional significance.

5.2 Graphical Results

The four moderation effects are visualised in Figures 2–5 using simple-slopes plotted at the mean and at one standard deviation above and below the mean of each moderator. Figure 2 (I4.0 × PRL → OE) and Figure 3 (I4.0 × PPL → OE) display the classic amplification pattern: at high values of the moderator, the slope of efficiency on I4.0 is markedly steeper. Figure 4 displays the contrasting pattern for resilience: the I4.0 → SCR slope is steepest at low PRL ($\beta\_simple \approx 0.305$) and is attenuated to near-flat at high PRL ($\beta\_simple \approx 0.036$). Figure 5 displays the strongest amplification: the I4.0 → SCR slope is mildly negative at low PPL ($\beta\_simple \approx -0.123$) and strongly positive at high PPL ($\beta\_simple \approx 0.464$).

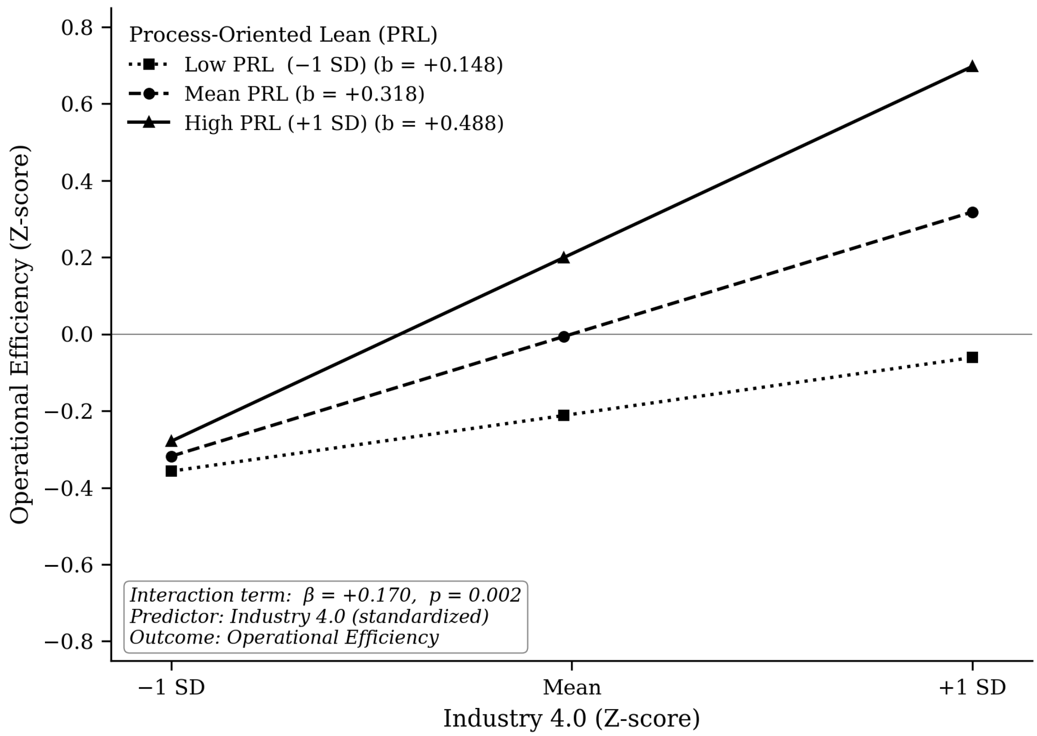


Figure 2. I4.0 × Process-Oriented Lean → Operational Efficiency.

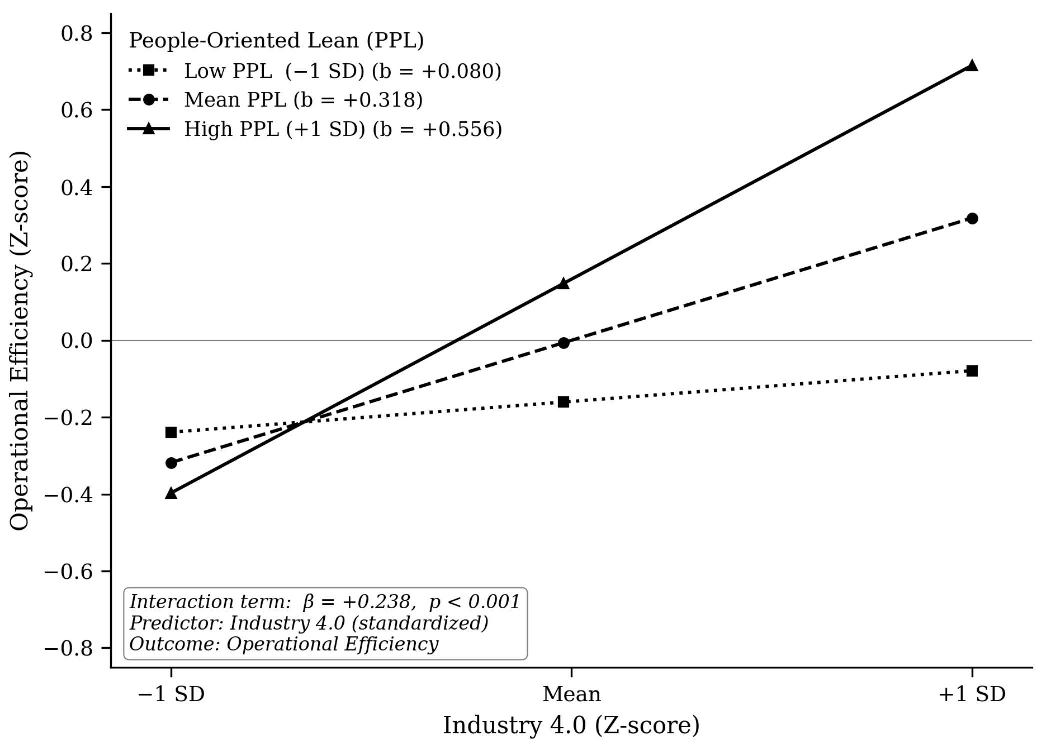


Figure 3. I4.0 × People-Oriented Lean → Operational Efficiency

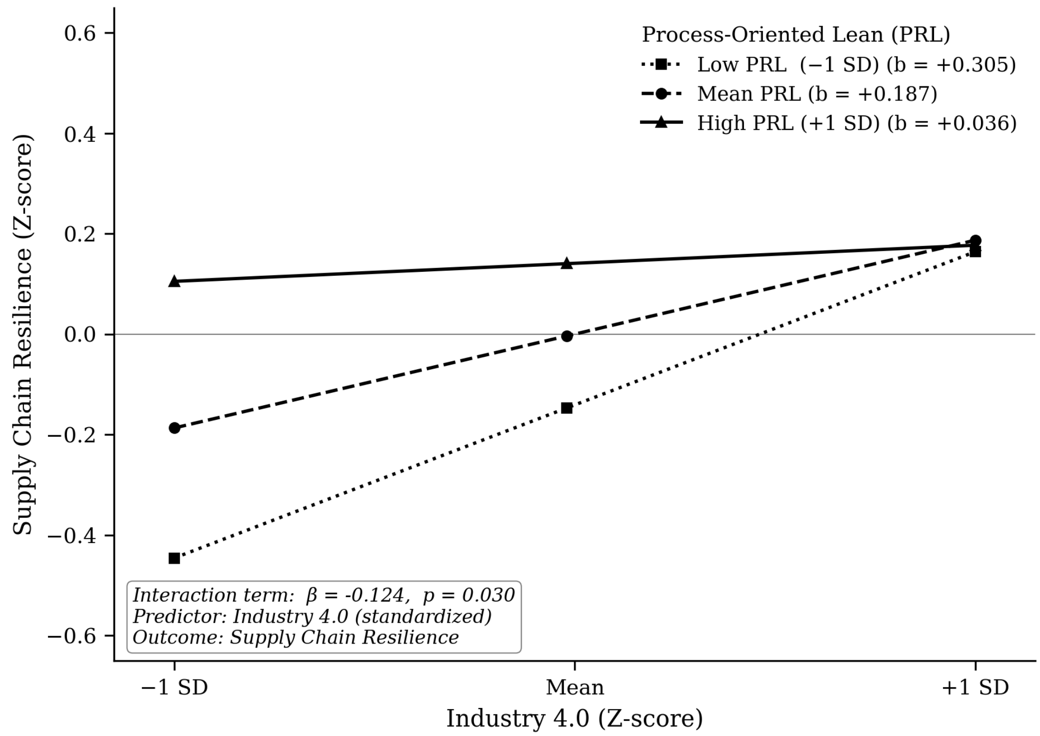


Figure 4. I4.0 × Process-Oriented Lean → Supply Chain Resilience

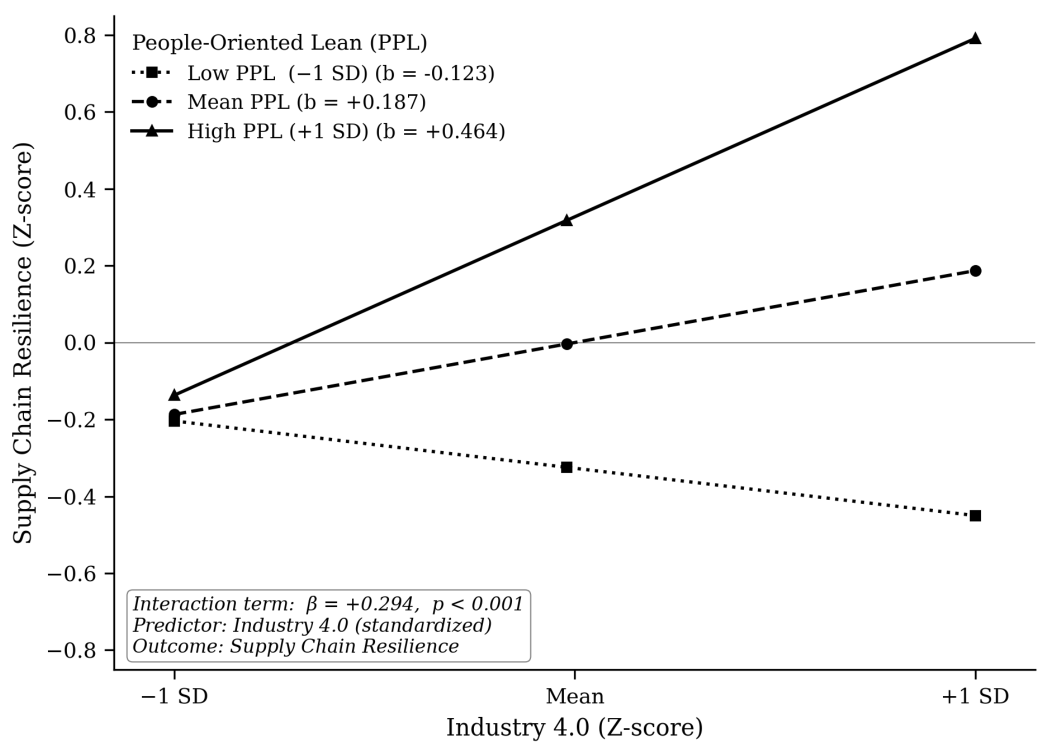


Figure 5. I4.0 × People-Oriented Lean → Supply Chain Resilience.

5.3 Proposed Improvements
Three managerial improvements follow directly from the findings. First, in Vision-2030 Saudi Arabia and in comparable emerging economies pursuing rapid digitalisation, executives should resist a technology-first framing of digital transformation. Investment in digital infrastructure is necessary but not sufficient. The empirical pattern indicates that, on average, the marginal investment in extending People-Oriented Lean—kaizen capability, cross-training, structured empowerment, gemba-based problem-solving—yields a larger improvement in resilience than the marginal investment in additional digital capability alone. Recent work confirms this pattern in adjacent contexts: I4.0 technology capabilities translate into supply chain resilience only through intermediate organisational capabilities such as innovation, collaboration, and visibility, rather than through technology investment alone (Huang et al. 2023; Nakandala et al. 2023).

Second, executives should be explicit about which outcome they are pursuing. Where the goal is purely operational efficiency, an aggressive Process-Oriented Lean plus I4.0 configuration is appropriate. Where resilience is on the agenda—as it must be for any serious supply chain after 2020—that configuration is dangerous unless deliberately balanced with People-Oriented Lean. The findings argue against reflexive across-the-board buffer elimination as a digital-transformation by-product. Steering committees for digital transformation should include workforce-development representation; performance dashboards should track both efficiency and resilience indicators (recovery time, supplier-substitutability, scenario-readiness); and capital-allocation decisions for new I4.0 investments should be conditional on a documented people-side implementation plan.

Third, for policymakers in Vision-2030 economies, industrial-policy support for digitalisation should be paired with workforce-development funding—vocational kaizen and continuous-improvement training, structured certifications in digitally enabled lean practice, and incentives for joint digital-and-organisational investments rather than digital investments alone. Subsidising sensors and analytics platforms without subsidising the human capacity to use them risks producing visible, measurable, but ultimately fragile supply networks. Recent Industry-5.0 and human-centric manufacturing frameworks similarly converge on this conclusion (Ghobakhloo et al. 2025; Peruzzini et al. 2023).

5.4 Validation
The structural model was re-estimated on two random split-half subsamples ($n_1 = 122$, $n_2 = 123$); the signs and significance of all six focal paths replicated, with the magnitudes of focal coefficients varying by less than 0.04 across splits. The model was further re-estimated excluding industry-sector dummies and excluding firm-size; coefficients of focal paths were essentially unchanged in both specifications. As an additional test, the negative I4.0 × PRL → SCR interaction was re-examined within the manufacturing subsample alone ($n = 85$); the sign and significance held ($\beta = -0.131$, $p = 0.039$), suggesting that the asymmetric moderation is not an artefact of cross-sector heterogeneity. Together, these checks support the stability and robustness of the headline findings.

6. Conclusion
This study tested an STS-grounded model of how Industry 4.0 technology adoption affects operational efficiency and supply chain resilience, and how the technical and social subsystems of Lean differentially moderate those effects, in a sample of 245 Saudi Arabian supply chain and operations managers. Three headline findings emerge. First, I4.0 has positive direct effects on both outcomes. Second, Process-Oriented Lean acts asymmetrically—it amplifies efficiency but attenuates resilience, providing the sharpest empirical articulation to date of the long-recognised lean-fragility thesis. Third, People-Oriented Lean amplifies both outcomes, with the strongest amplification on resilience, identifying social-subsystem investment as the bridging mechanism that converts digital visibility into resilience.

All three research objectives are met. The unique theoretical contribution is the demonstration that the STS joint-optimisation principle does not collapse to a uniform amplification logic across outcomes; rather, technical and social subsystems play asymmetric and outcome-specific roles. The unique empirical contribution is one of the first explicit tests of this asymmetric pattern in an emerging-economy context. The unique practical contribution is a defensible empirical foundation for re-orienting digital-transformation strategy in Vision-2030 economies away from technology-first reasoning and towards human-empowerment-anchored reasoning. The findings should generalise reasonably well to other GCC economies and to comparable middle-income economies pursuing rapid digital-industrial-policy agendas, where recent empirical work has documented similar I4.0–resilience dynamics in adjacent contexts (Alfaqiyah et al. 2025; Huang et al. 2023). Generalisation to mature-economy industrial settings, where the institutional context of digital transformation differs, requires further empirical verification. Limitations include the cross-sectional design, perceptual self-report measures, and treatment of I4.0 as a unidimensional bundle. Future research should employ longitudinal designs, multi-source measurement combining manager perception with archival operational data, sub-technology decomposition, and comparative emerging-economy studies.

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