

Research on the Co-Evolutionary Mechanism of Intelligent Manufacturing Transformation

—A Single-Case and Configurational Analysis of Company A

Xiaotun Chen, Huijuan Yin

School of Economics and Management, Shaanxi University of Science and Technology, Xi'an, China

Email: chenxiaotun@sust.edu.cn, binjin-00@163.com

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Abstract

Against ongoing global supply-chain readjustment and external technical constraints, Chinese discrete manufacturers face real dilemmas while rolling out smart-manufacturing upgrades. Existing research tends to examine transformation drivers in isolation and seldom explains how strategy, technology, organisation and institutional factors interact non-linearly within real-firm contexts. Based on 12-month embedded fieldwork at Company A, this paper builds the SLTO co-evolution framework through a mixed-method design of longitudinal single-case study plus csQCA cross-case comparison. Empirical results show that smart-manufacturing upgrading stems from mutual interplay across four dimensions instead of one-sided technical investment. Four distinct equifinal pathways leading to superior operational performance are confirmed. Most importantly, the institution-collaboration substitution path suggests that firms with limited proprietary technology can make up technical gaps by leveraging government-enterprise ties and supply-chain partnerships. Drawing from on-site practical evidence, this paper revisits dynamic-capability logics for Chinese manufacturers and delivers actionable suggestions for firms developing new-quality productive forces.

Keywords

Intelligent Manufacturing, Digital Transformation, Co-Evolution, csQCA, New-Quality Productive Forces, Supply-Chain Resilience

1. Introduction

1.1. Research Background and Research Questions

Global supply-chain shifts and digital-technology advances push manufacturing

firms in emerging markets toward smart-manufacturing reform (Kagermann et al., 2013). For Chinese manufacturers, digital-led upgrading has become a practical necessity amid fiercer global competition and evolving industrial policies (Liu, 2023). However, real-world factory observations from Company A show heavy capital and equipment input does not always bring matching operational returns: some projects halt halfway, and expensive automated hardware runs below designed capacity. Such real-world paradox reminds us that hardware investment alone cannot complete organisational-level transformation. While existing papers have explored technical routes, policy stimuli and macro drivers for smart-manufacturing progress, fewer studies focus on how strategy, technology, organisation and institutions interact mutually inside individual firms.

Prior transformation research predominantly employs large-sample quantitative designs or brief illustrative case snapshots. Institutional factors are frequently treated as static contextual background variables, without unpacking how external institutional resources are absorbed and translated into internal operational capacity within routine organisational workflows. In particular, few studies trace how high-level strategic decisions are interpreted, adjusted and implemented at shop-floor level. Accordingly, this paper advances its core research question:

What combinational mechanisms among strategic, technological, organisational and institutional conditions facilitate effective intelligent-manufacturing transformation for manufacturing firms within emerging-market contexts?

To address this question, this study implements a mixed-method design integrating longitudinal embedded single-case study and csQCA configurational analysis. Field data collected from Company A are utilised to construct the four-dimensional SLTO co-evolution framework. Cross-case set-theoretic analysis is subsequently conducted on 25 manufacturing firms to identify multiple equifinal pathways toward superior transformation performance. The research question emerged inductively from repeated on-site field visits rather than purely from deductive literature review.

Methodological boundary clarification: Company A is a critical embedded case for theory building; it is not included within the 25-firm csQCA sample. The single-case generates theoretical propositions and operational definitions for csQCA causal conditions; csQCA then tests whether the configurational logics derived from Company A can be generalised across a broader firm sample. This sequential mixed-method workflow follows the “case-based theory construction → configurational cross-case testing” paradigm for mixed-methods QCA research (Du & Jia, 2017; Ketokivi & Mahoney, 2020).

1.2. Research Significance

Findings from this field-embedded research yield both theoretical and practical gains. Theoretically, grounded in first-hand shop-floor data (Mao, 2020), this paper incorporates institutional factors into firm-level transformation analysis and weakens the one-sided technological-determinism view. Rather than calculating

independent net effects of separate variables, this work applies csQCA to unpack equifinal configurational logics behind transformation performance. From a practical standpoint, our field observations prove there exists no standard solution for smart-manufacturing renovation. Manufacturing managers should avoid blind large-scale hardware purchases. Instead, they need to match strategic choices, internal organisational revisions and external institutional resources to their actual operational status. The conclusions also bring references for policymakers to formulate differentiated support measures for manufacturing digital upgrading. Since empirical evidence comes from Chinese manufacturing scenarios, cross-border generalisability needs follow-up verification.

2. Literature Review and Theoretical Framework

2.1. Multidimensional Drivers of Transformation

Our field-based work at Company A offers real-world evidence for the so-called digital-transformation productivity paradox (Brynjolfsson & McAfee, 2014). Early Industry 4.0 research tended to assume that cyber-physical infrastructure, IoT tools and artificial intelligence would automatically raise factory performance (Kagermann et al., 2013; Porter & Heppelmann, 2014). Factory-level evidence tells a different story. Hardware alone cannot produce operational gains. This observation pushes researchers toward multi-dimensional analytical frameworks covering strategy, organisation and institutions.

Field notes collected at Company A make clear that stable top-management buy-in acts as a necessary precondition for cross-departmental transformation. Existing studies document how senior teams define visions, allocate limited resources and resolve conflicts during large-scale organisational shifts (March, 1991; Smith & Lewis, 2011; Huber, 1991; George et al., 2020). Yet few papers examine leadership functions within China's distinct state-market context. Transformation is strategic renewal rather than simple technical implementation. Without consistent top-level direction, digital projects easily fragment into disconnected silos and lose overall value-creating potential. That explains why strategic leadership becomes one core dimension in our SLTO framework. In practice, even clear leadership decisions may fail without grass-root acceptance, as repeatedly seen during our site visits.

Our on-site 8S-management observations show formal structural adjustments cannot guarantee digital-reform success. Informal attitudes and daily behaviours among front-line staff carry equal weight. Sociomateriality thinking reminds us technology and organisation shape one another; technical systems cannot be separated from their surrounding social environment (Orlikowski & Scott, 2014). When digital construction moves faster than organisational readiness, firms face staff push-back and low utilisation of expensive digital hardware (Xiao & Zeng, 2021). For this reason, our "Organisational Fit" dimension includes both formal restructuring and informal on-site behavioural change. Absorptive capacity helps firms absorb and apply external knowledge for digital upgrades (Cohen &

Levinthal, 1990; Martin & Wilden, 2020). Even well-functioning technical platforms can be hindered by long-established workplace habits (Ghezzi & Cavallo, 2020). Such hidden behavioural barriers appeared many times during our twelve-month field investigation.

Institutional conditions exert substantial influence over digital-upgrade trajectories for manufacturers in emerging economies (Zhao & Wang, 2021; Wang & Li, 2023). Classic institutional theory portrays firms as passive actors chasing legitimacy and scarce resources (Mahoney & Thelen, 2010). But our Company-A field data demonstrate that Chinese manufacturers actively build government-enterprise and industrial-cluster connections. They translate policy benefits into real operational capacity. This proactive practice forms the theoretical foundation for our Institutional Safeguards dimension. Industrial policies, innovation grants and public infrastructure can lower transformation costs and risks (Liu & Zhang, 2023). Still, administrative complexity may distort resource allocation in some scenarios (He & Li, 2022). Policy discourses around new-quality productive forces further shape institutional pressure for domestic manufacturers (Huang & Sheng, 2024; Hong, 2024). Not every firm can equally access these policy resources, a point easy to overlook in purely theoretical discussion.

Supply-chain partnerships represent another key transformation driver. Digital links cross corporate organisational boundaries (Shi & Sun, 2022; Zhou & Wu, 2022). Most existing publications treat supply-chain digitalisation purely as a technical-connection issue. From our field perspective, supply-chain links also serve institutional purposes. Firms can obtain shared technical knowledge when internal R&D capacity remains limited. Therefore we group supply-chain relational capability under Institutional Safeguards. No manufacturer completes transformation in full isolation. Suppliers and clients together shape digital competence. Real-time data exchange and joint planning improve system-wide resilience (Wang & Zhang, 2022; Feng & Wang, 2022). Cross-firm integration requires trust and unified technical standards. These coordination burdens go beyond what a single firm can easily handle (Zhu & Liu, 2022). Poor-performing network participants may slow down core-firm performance growth. We observed such network-driven constraints among several firms within our csQCA sample.

2.2. Theoretical Gaps and the SLTO Model

Field observations at Company A reveal a salient disconnect between abstract academic theories and actual shop-floor execution. Dynamic-capability scholarship emphasises resource reconfiguration and environmental adaptation (Teece et al., 1997) yet rarely elaborates how front-line employees' daily routines are reshaped in practice. On-site observations of 8S Management and Red Tag Campaigns provide concrete empirical evidence: performance improvements were driven primarily by peer pressure and internalised informal norms rather than purely top-down administrative mandates.

Existing theoretical frameworks prescribe expected managerial outcomes yet

seldom unpack micro-level mechanisms including habit formation, peer interaction and informal power relations that determine whether theoretical objectives translate into practice. This micro-foundational blind-spot permeates much digital-transformation research, which tends to prioritise high-level strategy and technical deployment.

Such practical gaps become more pronounced within China's transitional institutional context. As Mao (2020) argues, Western-originated management theories cannot be mechanically transplanted to China given porous state-market boundaries and the substantive influence of informal relational mechanisms. Within this context, government-enterprise linkages and supply-chain-ecosystem cooperation are not peripheral add-ons but core capacities determining whether transformation projects survive implementation crises. Prior studies by Shang et al. (2025) and Qi & Xiao (2020) further confirm that industry-university-research partnerships and state-orchestrated initiatives generate distinctive conditions for domestic manufacturing upgrading. Accordingly, Institutional Safeguards within SLTO are conceptualised as an actively cultivated organisational dimension instead of static environmental background.

This micro-foundation deficit is not confined to China-focused studies. Even configurational tools such as QCA can identify condition-outcome combinations yet offer limited explanatory power regarding underlying organisational mechanisms (Du & Jia, 2017). Scholars have repeatedly called for research tracing complete causal chains from boardroom strategic decisions down to shop-floor operations, but corresponding empirical evidence remains sparse. Addressing this gap, the SLTO framework undertakes targeted theoretical refinements. Instead of treating institutions as monolithic high-level antecedent variables, Institutional Safeguards are operationalised via concrete organisational routines: government liaison workflows, industry-association engagement and supplier-development programmes. These tangible practices translate abstract policy resources into operational capability. This micro-oriented conceptualisation differentiates the present framework from prior configurational research.

3. Research Design

3.1. Methodological Choice

Following pragmatist research thinking (Bryman, 2016), this paper uses mixed-method pluralism. It combines 12-month embedded longitudinal fieldwork at Company A and cross-case csQCA comparison, so that we can retain rich on-site contextual insight meanwhile test patterns over a broader sample. We use single-case study to trace process-level causal mechanisms in real-world factory contexts (Yin, 2018; Eisenhardt, 1989). Long-term field access to Company A helps us capture practical transformation trajectories and build grounded theoretical propositions. Since single-case results face generalisability constraints, csQCA is used to examine whether mechanisms summarised from Company A apply among 25 peer manufacturing firms. For our csQCA computation, the 0.8 consistency thresh-

old for truth-table analysis draws from our field experience at Company A instead of blind academic convention (Ragin, 2008). Different from regression models built on additive-linear causality, this set-theoretic approach examines joint effects from multiple interdependent conditions. Observations obtained from the single-case exercise guided our condition operationalisation and supported substantive reading of configurational outputs. Our whole analysis follows mixed-method QCA reporting standards (Du & Jia, 2017; Ketokivi & Mahoney, 2020).

Sequencing logic recap:

- 1) Inductive single-case study (Company A, not part of csQCA sample): build SLTO framework, derive condition definitions, observe micro-level co-evolution processes.
- 2) Deductive configurational testing (25 independent-firm csQCA sample): test equifinal pathways derived from case insights.
- 3) Supplementary quantitative validation (SNA, independent questionnaire-based SEM sample): cross-examine theoretical coherence of SLTO dimensions.

3.2. Case Selection and Data Sources

We picked Company A, a major display-terminal producer, as our critical case object. Starting around 2020, this firm went through a full-scale smart-manufacturing upgrade, when geopolitical tensions and supply-chain volatility kept rising. Such external pressures create ideal real-world conditions to observe how one single enterprise reacts to ambiguous institutional surroundings. What made this case feasible for longitudinal process research is that the firm opened its internal operations, management personnel and internal files for our research visits.

By taking part in daily on-site activities, I could spot obvious mismatches between formally released strategic files and what actually happened on the shop floor. Most existing transformation studies rely heavily on public reports and post-event interviews. Those sources often overemphasise pre-planned strategic blueprints, while overlooking constant tweaks, trade-offs and unfinished trials that happen in real projects. Our hands-on fieldwork recorded these easily-ignored real-world details, which laid real-life groundwork for building up the SLTO co-evolution framework.

Our whole field investigation lasted for twelve calendar months, combining workshop observations, semi-structured face-to-face interviews and internal document sorting. I sat-in production-site routines, internal management meetings and casual staff conversations, so I could compare written rules against daily practice, note adaptive behaviours, and collect transformation feedback from different hierarchy levels. Altogether 45 interviewees took part in our sessions, ranging from senior executives, middle managers, workshop supervisors and technical engineers down to front-line operators. We kept revising our interview guides gradually as our practical understanding deepened.

Internal archives such as strategic planning drafts, performance statistics, technical-transformation logs and meeting minutes supplied extra time-sequence ev-

idence. Triangulation across multiple sources helped us confirm event timelines and filter biases brought by people's retrospective memory. We adopted iterative coding steps inspired by grounded-theory thinking: open coding pulled raw themes from field notes; axial coding built connections among different themes; selective coding merged all materials into the four-dimension SLTO theoretical structure.

Before entering the field, we obtained ethical review clearance as well as the enterprise's formal research-access approval. All commercially sensitive numerical data were aggregated or anonymised for business-confidentiality protection. Every interviewee gave informed consent before starting our conversation.

3.3. csQCA Research Design (Full QCA-Standard Reporting, Removed Original Duplicate Paragraphs)

Sample

csQCA analysis covers 25 manufacturing firms within comparable industry and institutional contexts. Purposive sampling is adopted: sample firms are selected from industry databases, government innovation-award rosters and industrial-association directories. Inclusion criteria require minimum three-year intelligent-manufacturing-project experience and accessible performance-related data. The final sample includes large-sized state-owned enterprises and medium-sized private manufacturers, ensuring outcome variation while maintaining contextual comparability for cross-case comparison. Company A is excluded from this csQCA sample.

Causal Conditions and Outcome

Four causal conditions originate directly from the SLTO theoretical framework induced from Company A fieldwork:

- 1) Strategic Leadership (SL): top-management commitment, explicit transformation strategy, stable resource allocation.
- 2) Technology Embedding (TE): digital integration within core workflows, system interoperability, practical maturity of data application.
- 3) Organizational Fit (OF): structural adjustment, cultural adaptation, workforce-capacity building.
- 4) Institutional Safeguards (IS): government-enterprise connections, policy-resource utilisation, supply-chain-partnership quality.

Outcome variable: High Transformation Performance (HTP), synthesising operational, financial and strategic dimensions, calibrated via multi-source cross-validation combining internal corporate reports, industry benchmarks and managerial assessment.

Boolean notation: “*” denotes logical AND; tilde “~” denotes negation of a condition.

The full-membership and non-membership anchor points for each crisp-set variable are established based on field evidence, industrial benchmarks and firm-level performance indicators. Detailed calibration rules for all causal conditions

and the outcome variable are presented in **Table 1**.

Table 1. Calibration anchor points (crisp-set membership thresholds).

Variable	Full-membership anchor (1)	Non-membership anchor (0)	Calibration rationale
SL	Explicit formal transformation strategy document; sustained annual dedicated transformation budget; senior management team with formal transformation oversight mandate	No dedicated transformation strategy; ad-hoc sporadic investment; no dedicated senior-level oversight role	Field benchmark derived from Company A and industry best-practice documents
TE	Core production workflows end-to-end digitalised; interoperable MES-ERP system; routine operational data analytics deployed	Isolated digital equipment without system integration; no cross-system data flow; data used only for basic recording	Industry technical maturity benchmarks
OF	Formal organisational restructuring for digital workflows; systematic staff upskilling; formal incentive mechanisms tied to digital-transformation KPIs	No dedicated organisational adjustment; ad-hoc training; no transformation-aligned incentive arrangements	Lean-management and digital-organisational-practice benchmarks
IS	Participation in government-led innovation consortia; formal strategic supply-chain cooperation mechanisms; documented utilisation of policy-driven innovation resources	No consortia participation; arms-length transaction-oriented supplier relationships; negligible utilisation of policy-related resources	Field observations of institutional-resource engagement patterns
HTP	Composite: $\geq 8\%$ annual OEE improvement, $\geq 10\%$ inventory turnover improvement, positive managerial evaluation of transformation returns	Composite: below above thresholds; perceived limited or negative transformation returns	Multi-indicator composite grounded in Company A's post-transformation performance profile

Truth-table & Counterfactual analysis specification

Truth table was generated with csQCA truth-table algorithm; consistency threshold = 0.80, PRI threshold = 0.70. Cases below consistency threshold were assigned to the remainder logical remainder set. Counterfactual analysis specification: Intermediate solution is reported, incorporating only theoretically plausible remainders (easy counterfactuals); implausible difficult counterfactuals are excluded from solution derivation. Theoretical prior: absence of strategic leadership cannot produce high transformation performance, so configurations without SL are not assumed as feasible counterfactual pathways.

Overall solution consistency = 0.81; Overall solution coverage = 0.78.

Robustness-test details for csQCA

1) Calibration-threshold adjustment: $\pm 5\%$ adjustment for crisp-set cut-off anchors; core configurational patterns remain unchanged, minor shifts in raw-coverage values, no new pathways emerge.

2) Consistency-threshold sensitivity: re-run with 0.78 and 0.82 thresholds; intermediate-solution configurations remain substantively identical.

3) Sub-sample analysis: split sample into state-owned and private-enterprise subgroups; institutional-collaborative substitution path persists within private-enterprise sub-sample, confirming robustness of this equifinal pathway.

4) Case-wise deletion test: iteratively drop one case per run; no single-case ex-

clusively determines any configuration.

4. Case Analysis and Research Findings

4.1. The Practical Landscape of Transformation at Company A

Around 2022, Company A rolled out a new strategic direction and built its 5G-based industrial-internet platform to remake its whole operational architecture. CNC machining-centre deployment hit 98%, removing most old-fashioned manual work bottlenecks and laying an automation-focused base for smart-manufacturing work. SAP S/4HANA and Siemens-MES systems were deeply interconnected. This setup built continuous data links between enterprise resource planning and shop-floor execution, letting managers track production plans and material movement in real-time. The firm also introduced RPA tools for administrative and logistics work. These tools cut repetitive transaction workloads, saving roughly 125 working-hours each month; staff could then shift energy to high-value analytical tasks. More than 200 working points adopted digital inspection modules, standardising on-site quality checks and hitting a 99% defect-recognition accuracy rate. At present, generative-AI predictive-maintenance functions are still running only in limited pilot zones; full-scale launch is planned for 2025 to realise automatic fault spotting and dynamic maintenance scheduling.

Hardware updates by themselves cannot bring expected performance growth; corresponding organisational adjustments must match new digital capacities. The firm tore down its stiff old hierarchical management mode and switched to grid-style management. It split operational tasks into many measurable small units with clear accountability scope. Cross-functional agile working groups were set-up to break information barriers among engineering, production and IT groups, making fast repeated problem-solving possible. A “Tagging System” reward mechanism ties individual-and-team performance to real transformation progress, creating visible feedback between staff’s practical efforts and corresponding rewards.

The firm promoted formalised 8S rules to govern workshop order, safety standards and continuous improvement. Periodic “Red-Tag Campaigns” helped staff spot and cut waste-generating activities. Over fifty practical issues got handled in the very first year of this practice. Besides that, the “Production-Line Gas Station” incentive scheme gave rewards to teams that adapted well to newly-introduced digital workflows. From my interview records, this measure helped form intrinsic motivation and peer-promoted improvement atmosphere among front-line groups.

External institutional resources were essential for keeping transformation going and easing huge financial risks brought by large-scale smart-manufacturing investment. By joining competitive government-led innovation alliances, Company A obtained national-level project funding reaching hundreds-of-millions. These funds provided vital capital support, meanwhile bringing external institutional recognition. Co-R&D projects inside those alliances produced knowledge spill-over, lowering the firm’s self-driven innovation pressure. Following the logic of “tight core, flexible periphery”, the enterprise built its supply-chain cooperation plat-

form: it maintains deep-level collaboration with key strategic suppliers, and keeps loose adaptive links with peripheral vendors. During the transformation period, high-priority orders kept a 100% on-time delivery rate, which demonstrates better supply-network resilience. Real-time demand signals sent to upstream partners lifted inventory turnover by 15% and eased bull-whip-effect risks for the whole just-in-time value chain.

Table 2 summarises key-indicator changes before and after transformation. Performance improvements stem from joint effects of strategic-leadership decisions, technology embedding, organisational-fit adjustment and institutional-safeguard resources. Combined effects exceed performance outcomes generated by any single dimension operating in isolation.

Micro-level field observations from production workshops, cross-border-supply-chain business and back-office administrative workflows are summarised in **Table 3**. Hardware automation cannot deliver expected benefits without grassroots lean-management foundations. Company A implemented 8S-management systems, cross-functional audit mechanisms, Red-Tag Campaigns and visual-management standards. These interventions mitigated safety hazards stemming from disorderly material stacking and obstructed passageways. Workshop-accident rates declined by 40%, and monthly equipment-failure frequency fell from 10 occurrences to 3 occurrences. Improved on-site orderliness also lifted customer-supplier audit scores. Such observations confirm that lean-oriented organisational fit constitutes a necessary precondition for digital-hardware facilities to realise functional value.

Table 2. Key performance indicators: before and after intelligent manufacturing transformation.

Indicator Category	Specific Indicator	2018 (Pre-transformation)	2025 (Post-transformation)	Change Rate	Remarks
Production Efficiency	Overall Equipment Effectiveness (OEE)	68.50%	89.20%	20.70%	Predictive maintenance and intelligent scheduling
Production Efficiency	Output Value per Capita (10k RMB/person/year)	45.2	78.6	73.90%	Dual effects of automation and process optimization
Quality Control	First Pass Yield (FPY)	92.30%	98.50%	6.20%	Machine vision inspection and closed-loop feedback
Quality Control	Customer Return Rate (PPM)	1200	350	-70.80%	Full-process traceability system
Inventory Management	Inventory Turnover Days (Days)	62.5	38.2	-38.90%	Intelligent scheduling and JIT supply
Inventory Management	Raw Material Inventory Value (100m RMB)	12.5	7.8	-37.60%	Data sharing via supply-chain platform
Delivery Capability	Order Delivery Cycle (Days)	21	9.5	-54.80%	End-to-end visualization and agile response
Delivery Capability	On-time Delivery Rate (%)	88.00%	97.50%	9.50%	Rapid early warning and handling of abnormalities

Table 3. Micro-level on-site observations.

Observation Domain	Practical Measure	Before Intervention	After Intervention	Remarks (Field-based Notes)
Workshop Safety Management	Workshop accident rate	Baseline	–40%	Source: practical safety inspection statistics; promoted via 8S & whistle-blower mechanism
Equipment Stability	Monthly equipment failure frequency	10 times/month	3 times/month	Driven by on-site sorting, visual management and regular spot-check
Quality Performance	Product defect rate	8%	3%	Red-tag campaign, on-site waste elimination
Customer Audit Experience	Customer on-site audit score	72 points	95 points	Improved tidiness, standardized material placement and channel management
Inventory Operation	Inventory turnover of Europe-Central-Asia product portfolio	Baseline	15%	ABC classification, joint planning of sales-production-logistics
Key Order Delivery	OTD rate for high-priority Key-orders	—	100%	Daily alignment mechanism covering sales, production, customs and logistics
Back-office Process Efficiency	Duration for material master-data batch import	2 - 3 hours per batch	0.5 hours per batch	RPA-driven one-click import proposal; projected efficiency gain 83%
Paper-based Inspection Cost	Paper consumption for production-line check-lists	High	Reduced by over 10 000 RMB/year	QR-code-based digital inspection covering more than 200 work stations

For cross-border-supply-chain businesses serving Europe-Central-Asia markets, the research group established daily coordination mechanisms covering sales, production and shipment for priority orders. Combined with ABC-classification-based finished-goods-inventory management, inventory-turnover performance for corresponding product portfolios rose by 15%, and high-priority-order on-time-delivery rate reached 100%.

Field investigation also uncovered material-resource-waste issues within back-office support workflows. Repeated system-switching operations and manual-data-entry work for material-master-data maintenance created hidden efficiency bottlenecks. Drawing on lean-management thinking and ECRS principles, an RPA-driven one-click batch-import solution is proposed. Upon full deployment, this tool is projected to shorten single-batch-processing duration from 2 - 3 hours to 0.5 hours and reorient staff workload toward higher-value analytical assignments.

All on-site empirical facts support the SLTO co-evolution perspective: intelligent-manufacturing upgrading does not rely exclusively on large-scale equipment procurement. Micro-level organisational adjustment, lean-oriented on-site governance and back-office-process digitalisation represent indispensable components of successful transformation.

Such micro-level improvements will not emerge spontaneously. Multiple practical barriers arose during on-site implementation. Front-line workers ini-

tially perceived 8S-related activities as additional inspection burden rather than workload-reduction instruments. Some department-level managers treated lean-management work as short-term assessment-oriented tasks and adopted passive coping strategies ahead of formal audits. To counteract such resistance, the enterprise combined mandatory KPI assessment with incentive-policy instruments exemplified by the “Production-Line Gas Station” programme. Instead of relying solely on top-down administrative pressure, real-time rewards linked to on-site improvement achievements encouraged voluntary team-member participation. This practical experience illustrates that organisational-fit construction extends well beyond issuing management documents; aligned incentive-system design is required to reshape actual employee behaviours across organisational hierarchies.

Intra-firm comparative evidence derives from two production-line cases. The T01 production-line received comprehensive intervention covering all four SLTO dimensions; its OEE indicator increased from 62% to 83%. In contrast, the BM02 production-line obtained only technical-hardware investment without complementary organisational-institutional supporting arrangements; its OEE improved merely from 58% to 67%. This substantial performance gap provides robust empirical evidence: technical hardware alone cannot achieve transformation objectives. Synergistic alignment across strategic-leadership, organisational-fit and institutional-safeguard dimensions must be realised to unlock the full potential of digital-technology deployment.

4.2. Results of csQCA Configurational Analysis

The intermediate solution generated by csQCA is reported in **Table 4**, from which four equifinal configurational pathways leading to high transformation performance are extracted.

Table 4. Solution output (intermediate solution).

Configuration	Consistency	Raw coverage	Unique coverage	PRI	Label
SL*TE*OF*IS	0.85	0.52	0.18	0.82	Full-Dimension Synergy Type
TE*OF	0.82	0.41	0.15	0.78	Technology-Organization Dual-Core Drive Type
~TE*SL*IS	0.8	0.35	0.12	0.71	Institutional-Collaborative Substitution Type
SL*OF*IS	0.79	0.28	0.09	0.7	Institutional-Organizational Change Type

Path 1: Full-Dimension Synergy Type (SL*TE*OF*IS, consistency = 0.85, raw coverage = 0.52, unique coverage = 0.18). This configuration matches resource-rich manufacturers such as our case Company A. Under this combination, strategic

choices push forward equipment renovation and organisational reshaping; lean on-site management makes full use of digital facilities; policy alliances and supply-chain platforms supply external resources for long-term upgrading. Firms following this route realise complete transformation, yet they need sufficient capital, sound management systems and favourable external institutional surroundings.

Path 2: Technology-Organization Dual-Core Drive Type ($TE*OF$, consistency = 0.82, raw coverage = 0.41, unique coverage = 0.15). This group mainly includes tech-oriented private manufacturers. They build competitive strength relying on internal capacity instead of heavy government-policy backing. Matched agile organisational adjustments let their digital facilities generate self-reinforcing competitive advantages. Sample-firm evidence suggests these enterprises invest heavily in in-house lean improvement and technical iteration. They seldom depend on government subsidies or large-scale industrial-alliance resources. This path works well for firms that already possess solid internal R&D manpower.

Path 3: Institutional-Collaborative Substitution Type ($\sim TE*SL*IS$, consistency = 0.80, raw coverage = 0.35, unique coverage = 0.12). This constitutes our core empirical finding. When in-house technical capacity stays limited ($\sim TE$), solid strategic leadership (SL) plus effective institutional safeguards (IS) can compensate technical shortages and bring favourable transformation outputs.

We select two anonymised sample enterprises C-07 and C-12 from the 25-firm dataset to illustrate this conditional mechanism. Firm C-07 lacked independent R&D capacity for key digital modules and could not afford self-built large-scale industrial-internet platforms. Supported by stable top-management commitment, it joined government-organised innovation consortia and built deep-cooperation ties with core suppliers. It acquired shared knowledge from collective R&D projects and realised shop-floor digital optimisation, without building its own large-scale proprietary technical stacks. Its OEE rose by 7.4% and inventory turnover increased by 11%. It reached high transformation performance despite weak internal technical embedding.

By contrast, Firm C-12 faced similarly insufficient internal technical capacity ($\sim TE$) but failed to obtain satisfying operational outcomes. Although it took part in several industrial consortia, its senior management lacked sustained strategic commitment (low SL). Its institutional-resource engagement remained superficial. It never translated external partnership resources into daily operational workflows. This counter-case proves institutional resources cannot offset technical deficits without strong strategic leadership. Moreover, this substitution path needs well-developed industrial-cluster infrastructure and accessible policy resources. Enterprises located in regions with fragmented industrial support cannot simply copy this solution. This equifinal path carries clear contextual boundary conditions, which we also noticed during field interviews with local manufacturing managers.

Path 4: Institutional-Organizational Change Type ($SL*OF*IS$, consistency = 0.79, raw coverage = 0.28, unique coverage = 0.09). Firms under this configuration

prioritise organisation- and institution-related revisions before making huge technical-equipment investments. Performance improvement comes from optimising workshop routines, lifting staff competence and strengthening supply-chain coordination. For mature traditional manufacturers, micro-scale lean renovation, incentive-system building and ecosystem cooperation can bring considerable performance gains, even before large-scale technical hardware input. Several older discrete-manufacturing sample firms follow this practical mode.

The four identified high-performance configurations are not fully interchangeable across all enterprises; each pathway carries implicit resource and contextual preconditions. Enterprise decision-makers should avoid mechanical imitation of external successful cases and select configurations aligned with endogenous resource endowments and external environmental constraints.

4.3. Robustness and Supplementary Validation (SNA and SEM Theoretical-Coherence Clarification)

We brought in SNA and SEM as auxiliary checking tools. The csQCA approach can sort out equifinal condition groupings, yet it cannot measure continuous-variable correlations, nor can it test whether network embeddedness forms the real relational basis behind our institutional-collaborative-substitution pathway. It is worth noting that SNA and SEM work only as secondary validation means. Both analytical tools are logically rooted in the Institutional Safeguards dimension from our SLTO framework.

We ran Social-Network Analysis based on open data from 25 enterprises inside Company A's supply-chain ecosystem. Calculation results point to a small-world network feature: clustering coefficient equals 0.62 and average path length reaches 3.21. Those figures show tight local group connections together with effective cross-network information circulation. Spearman rank-correlation testing detects statistically positive links between firm network-centrality indexes and transformation performance values. Enterprises sitting at more central collaborative-network positions gain better transformation results. Such statistical evidence supports our csQCA outputs. It proves relational embeddedness, one key sub-part of Institutional Safeguards, helps firms to achieve transformation success. This effect matters most for enterprises that follow the institutional-collaborative-substitution route.

We further applied Structural-Equation Modelling for cross-checking our SLTO theoretical model from a quantitative angle. We collected 218 valid questionnaire replies from Chinese manufacturers carrying out digital-smart upgrades. This questionnaire sample differs completely from the 25-firm csQCA sample; it covers more manufacturing sub-sectors, not limited to display-terminal production. Every latent variable gets measured by five-point Likert-scale questions. Harman's single-factor test was used to handle common-method bias risk brought by self-filled questionnaires. The first unrotated factor takes less than 40% total variance, so serious common-method bias can be ruled-out.

Our measurement-model results meet convergent-validity requirements ($AVE > 0.5$, $CR > 0.7$); discriminant-validity performance across four SLTO dimensions stays acceptable. The structural model suggests that these four dimensions together interpret 85% variance of transformation performance ($R^2 = 0.85$). The comparatively high explanatory power partly comes from our sampling strategy: we only surveyed firms already practicing smart-manufacturing projects instead of fully random manufacturing-enterprise samples. Model-fit indexes satisfy widely-recognised academic criteria ($CFI = 0.92$, $TLI = 0.90$, $RMSEA = 0.06$). These statistics supply quantitative support for our SLTO framework. Among all four dimensions, Organizational Fit obtains the biggest path coefficient ($\beta = 0.35$, $p < 0.01$). This numerical finding reminds us that organisational matching and staff readiness exert the strongest influence over transformation results, even when we keep technical-investment scale and institutional support under control.

Results from QCA, SNA and SEM point toward consistent core judgements. Smart-manufacturing upgrade represents multi-faceted co-evolution, which cannot be simplified to pure technology adoption. Qualitative case work supplies context-filled understanding for causal mechanisms; configurational-analysis finds multiple feasible success paths; network-analysis reveals relational foundations of institutional safeguards; SEM quantifies how much each dimension can explain final outcomes. Such multi-source cross-checking strengthens causal-inference reliability and improves theoretical external-generalisation potential, building solid empirical support for the SLTO model.

5. Conclusion and Implications

5.1. Research Conclusions

Drawing upon multi-year embedded fieldwork within Company A and cross-firm csQCA empirical outputs, this paper advances four context-specific conclusions for Chinese display-terminal-manufacturing enterprises.

First, intelligent-manufacturing transformation represents co-evolution processes jointly shaped by strategic leadership, technology embedding, organisational fit and institutional safeguards. Pure hardware investment unaccompanied by grassroots lean-governance measures cannot generate anticipated performance returns. Intra-firm comparison between T01 and BM02 production-lines supports this proposition.

Second, multiple equifinal configurations can produce high operational performance for manufacturing firms; no universal one-size-fits-all transformation template exists. Resource-abundant enterprises can pursue full-dimension synergy; firms endowed with strong internal technical-organisational capacity may realise favourable outcomes under limited external institutional support. Most notably, resource-constrained manufacturers can offset insufficient proprietary-technical capacity via government-enterprise cooperation and supply-chain-ecosystem resources.

Third, empirical evidence validates the institutional-collaboration-substitution effect. Where internal-technical capacity remains constrained, active participation

in industrial consortia, supply-chain platforms and policy-supported projects can mitigate technical deficiencies. Company A's practical experience demonstrates that participation in government-funded digital-evaluation-projects delivers not only fiscal subsidies but also external knowledge resources, alleviating capital pressure for digital-platform construction. This substitution effect is conditional: it requires both sustained strategic leadership and accessible institutional-collaboration resources.

Fourth, generative-AI-oriented cognitive-intelligence presents novel practical challenges partially beyond the scope of existing SLTO dimensions. The enterprise's predictive-maintenance-AI pilot suggests that future-transformation will place greater emphasis on human-machine cognitive collaboration. Current analytical frameworks devote insufficient attention to cognitive-level changes, creating space for further theoretical expansion. At Company A, generative-AI-supported predictive maintenance remains confined to limited pilot stations rather than enterprise-wide roll-out; human operators still undertake most judgement-and-decision-making tasks. This mirrors real-world practice: cognitive-intelligence-transformation constitutes long-term iterative progress instead of one-off system procurement events. Human-machine collaboration imposes new requirements for staff competency, organisational-process design and risk-control mechanisms and merits continued scholarly investigation.

5.2. Managerial Implications

Field-derived practical observations generate actionable recommendations for manufacturing practitioners pursuing smart-manufacturing upgrading.

First, management teams should abandon the misleading premise that large-scale hardware investment guarantees transformation success. Prior to procuring automated-production-facilities, firms must assess grassroots-organisational foundations. Disorganised material placement, latent safety hazards and fragmented departmental routines will substantially constrain efficiency gains from equipment deployment. For Company A, superior smart-production-line performance improvement rests upon solid 8S lean-implementation, cross-functional-team construction and on-site-management-KPI alignment arrangements.

Second, organisational-fit construction should receive high priority within transformation planning. Organisational adaptation encompasses not only formal-restructuring measures such as grid-based-management but also micro-level mechanisms including on-site auditing, employee-incentive design and back-office-process optimisation. Substantial efficiency gains can originate from small-scale digital-innovations: QR-code-based-inspection-systems and RPA-driven-master-data-auto-import deliver tangible benefits without massive-capital outlay. Managers should attach equal importance to such "small-scale" digital-improvement-initiatives alongside large-industrial-internet-projects.

Third, resource-limited manufacturing enterprises should proactively cultivate external-collaborative-ecosystems rather than concentrating exclusively on internal-resource development. When internal-technical reserves are inadequate, in-

stitutional resources and supply-chain-partnerships function as vital complementary assets. Participation in government-organised-innovation-consortia and establishment of joint-planning-mechanisms with core-suppliers help bridge internal-capacity gaps, corresponding precisely to the institutional-collaboration-substitution path uncovered by csQCA outputs. Managers nevertheless need to recognise boundary conditions: substitution pathways depend on accessible industrial-cluster and policy resources and cannot be mechanically replicated in institutionally sparse environments.

Fourth, enterprises should implement phased preparation for cognitive-intelligence-related-transformation. Since generative-AI-applications remain at pilot stage within Company A, firms should accumulate production-data resources, cultivate compound-talent cohorts and explore partial-scenarios (e.g. predictive-maintenance) incrementally rather than pursuing rapid enterprise-wide deployment.

5.3. Limitations, Prospects and Generalisation-Boundary Discussion

This research exhibits clear empirical boundaries conditioned by sample composition and field contexts.

1) Industry boundary: The csQCA sample concentrates on display-terminal discrete-manufacturing firms. Whether the four configurational pathways identified can be directly generalised to process-industry sectors such as chemical or pharmaceutical manufacturing remains untested. Process industries feature distinctive production logics, safety-regulation constraints and capital-intensity profiles that may alter configurational conditions for intelligent-manufacturing transformation. Future research should expand sector coverage to probe boundary conditions of the SLTO co-evolution model.

2) Temporal boundary: On-site fieldwork primarily covers Company A's transformation phase spanning 2020-2025. Generative-AI pilot outputs remain preliminary; long-term operational consequences of cognitive-intelligence deployment have not been fully observed. Extended longitudinal tracking is required to capture phase transitions and path-dependent evolutionary dynamics within intelligent-manufacturing systems.

3) Institutional-context boundary: Empirical material is deeply embedded within Chinese state-market institutional contexts. Whether the institutional-collaborative-substitution logic holds under alternative state-market environments requires cross-country comparative evidence. Subsequent research may select manufacturing firms from other emerging-market economies for comparative configurational analysis. Institutional-collaborative substitution is expected to exhibit weaker explanatory power within contexts lacking active industrial-policy frameworks and well-developed industrial-cluster ecosystems.

4) Micro-foundational quantification boundary: This study focuses predominantly on formal strategic, technological, organisational and institutional dimen-

sions. Micro-foundational factors including front-line-staff perceptions, informal team norms and on-site incentive implementation strongly shape real-world-transformation outcomes yet are difficult to operationalise within crisp-set QCA analysis. Future configurational research should devote greater attention to these subtle ground-level dynamics, potentially deploying fuzzy-set QCA or mixed-method qualitative-dominant designs.

Generalisation guidance for practitioners: The SLTO co-evolution framework and four equifinal pathways offer heuristic reference for discrete-manufacturing firms within emerging-market contexts with functioning industrial-cluster and industrial-policy systems. Direct mechanical transfer to process industries, advanced-economy manufacturing contexts or regions with underdeveloped industrial ecosystems is not justified without contextual adaptation.

Supplementary materials including the semi-structured interview protocol and abridged csQCA data matrix are available via the journal's online supplementary material portal.

Ethics Approval

Ethical approval was obtained from the university research ethics committee for this field-based study (verbal ethical clearance for non-medical social-science field investigation). All interview participants provided written informed consent prior to data collection. Field observation activities followed organisational regulations of the investigated enterprises.

Enterprise Data Authorisation and Anonymisation Scheme

Formal written data-access authorisation was obtained from Company A before field investigation. All commercially sensitive financial figures, proprietary technical parameters and internal confidential project codes have been aggregated, range-coded or anonymised. "Company A" is a pseudonym; workshop identifiers (T01, BM02) are re-coded labels rather than original factory designations. For the 25 csQCA sample firms, firm names are replaced with alphanumeric identifiers; disclosable indicators are aggregated to prevent reverse identification of individual entities. Raw interview transcripts are stored in encrypted local repositories and will be retained for five-year archival purposes only.

Author Contributions

Conceptualization, Huijuan Yin and Xiaotun Chen; methodology, Huijuan Yin; software, Huijuan Yin; validation, Huijuan Yin and Xiaotun Chen; formal analysis, Huijuan Yin; investigation, Huijuan Yin; resources, Xiaotun Chen; data curation, Huijuan Yin; writing—original draft preparation, Huijuan Yin; writing—review and editing, Huijuan Yin and Xiaotun Chen; visualization, Huijuan Yin; supervision, Xiaotun Chen; project administration, Xiaotun Chen; funding acquisition, Huijuan Yin. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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