

Article

Research on the Technology–Organization–Environment Matching Mechanism in the Digital Transformation of the Manufacturing Industry: Evidence from Frontline Employees in the Guangdong–Hong Kong–Macao Greater Bay Area

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Abstract

Amid China's "Manufacturing Power" push, full-chain digital restructuring in the Guangdong–Hong Kong–Macao Greater Bay Area remains hampered by mismatches among technology, organization, and environment. We therefore explored how shop floor actors perceive and shape this Technology–Organization–Environment (TOE) interplay. Semi-structured interviews with frontline operators, maintainers, and supply chain staff from GBA manufacturers were inductively coded, yielding 36 concepts, 10 categories, and 3 core TOE aggregates that were woven into a grounded model. The analysis shows that industrial internet platforms and smart equipment only create value when matched by flexible shop floor structures, cross-department data protocols, and skilled teams; otherwise, data silos, simulation–production deviations, and "buy-but-not-build" procurement stall adoption. Market pressure for customized, short-lead-time products and divergent municipal pilot policies further intensify the TOE balancing act, particularly for SMEs with weak absorptive capacity. By revealing a grassroots "technology-driven → organization-adapted → environment-adjusted" spiral that is moderated by frontline feedback, the study extends the TOE framework to micro-level, regional innovation theory and offers policy–practice levers for differentiated, cross-city manufacturing upgrading.

Keywords: digital transformation; manufacturing industry; Technology–Organization–Environment matching; industrial internet; Guangdong–Hong Kong–Macao Greater Bay Area

1. Introduction

The global digital wave and China's "Manufacturing Power" strategy have pushed manufacturing firms to move from isolated equipment upgrades to full-chain digital restructuring that integrates R&D, production, supply chains, and services (W. H. Wu et al., 2023). The Guangdong–Hong Kong–Macao Greater Bay Area (GBA) now hosts more than 500 smart factories and leads the country in both smart manufacturing penetration and policy intensity (C. Q. Wu et al., 2022). Empirical evidence shows that big data, AI, and blockchain can significantly optimize manufacturing structures, but only when they are simultaneously matched by organizational process re-engineering and environmental dynamism (Qin & Huang, 2024; Li et al., 2022).

Despite these macro-level insights, three critical gaps remain. First, most studies focus on top-management strategy or firm-level configurations, leaving the micro-behaviors of



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operators, maintainers, and supply chain staff—the actual “technology users”—largely unexplored (Ghobakhloo et al., 2022). Second, although the Technology–Organization–Environment (TOE) framework has been widely adopted, its empirical applications rarely dissect how the three dimensions are dynamically balanced from the shop floor upward (Hoang, 2024; Shukla & Shankar, 2021). Third, regional heterogeneity inside the GBA (divergent subsidy rules across Guangzhou, Shenzhen, and Foshan) and volatile cross-border supply chains create contradictory pressures: customized C2M demand pulls for flexible production, while logistics uncertainty pushes for tighter digital integration (Na & Li, 2021; Zhang et al., 2022). Whether frontline acceptance acts as a bottleneck or a catalyst in this tug of war is still contested (Jewapatarakul & Ueasangkomsate, 2024).

This study addresses these controversies by investigating how frontline employees in GBA manufacturing clusters perceive, enact, and feedback on TOE synergy. Using grounded theory and semi-structured interviews with frontline personnel, we construct a micro-level TOE matching model that reveals a “technology-driven → organization-adapted → environment-adjusted” spiral. The principal conclusion is that shop floor feedback loops determine whether digital infrastructure translates into sustained performance gains or remains an under-utilized asset, especially for SMEs that face insufficient absorptive capacity and rising compliance costs.

2. Theoretical Framework

The Technology–Organization–Environment (TOE) framework asserts that the adoption and value realization of technological innovation are simultaneously shaped by three inter-dependent contexts: technological assets, organizational capabilities, and environmental pressures (Tornatzky et al., 1990). In contemporary manufacturing research, TOE has evolved from a main-effect lens to a configurational paradigm that stresses “alignment”, “fit”, or “synergy” among the three dimensions (Li et al., 2022; Shukla & Shankar, 2021). Empirical studies confirm that only bundles of high-tech investment, agile structures, and dynamic market conditions generate super-additive performance gains, whereas isolated initiatives frequently fail (Qin & Huang, 2024; W. H. Wu et al., 2023).

Nevertheless, two theoretical limitations persist. First, the extant TOE literature largely operates at the firm or strategic business unit level, treating adoption as a top-down decision and black-boxing the micro-processes through which technologies are enacted, resisted, or re-invented on the shop floor (Ghobakhloo et al., 2022; Hoang, 2024). Second, although scholars acknowledge that frontline employees are the ultimate “technology carriers”, few studies have explicitly theorized how operators’, maintainers’, and supply chain staff’s interpretive schemes feed back into the organizational and environmental contexts (Jewapatarakul & Ueasangkomsate, 2024; Niu et al., 2024). This omission is consequential because digital manufacturing systems—MES, digital twins, and industrial internet platforms—require real-time sense-making and discretionary adjustments that formal procedures cannot fully specify (Y. Chen et al., 2024; Koumas et al., 2021).

To close this gap, we integrate grounded theory with TOE. Grounded theory is explicitly designed to uncover latent social processes and behavioral mechanisms that link structural conditions to emergent outcomes (X. M. Chen, 2000). By inductively coding frontline narratives, we can articulate a process model that positions employees as active mediators: their technological sense-making shapes immediate usage patterns; their collective problem-solving re-configures organizational routines; and their voiced frustrations or improvisations become signals to which external suppliers and policy makers subsequently adapt (Vladimirov & Harizanova, 2025; Zhang et al., 2022).

3. Materials and Methods

3.1. Research Setting and Sample

The study was conducted in the Guangdong–Hong Kong–Macao Greater Bay Area (GBA), China’s largest manufacturing hub, which comprises 9 + 2 cities with highly inter-dependent supply chains. Eighteen enterprises were purposefully selected to cover four strata defined by industry (automotive, electronics, machinery, and textiles) and size (5 large, 8 medium, and 5 small). Within each plant, gatekeepers helped identify the single employee who “most directly interacts with the new digital system every day.” The final convenience/availability sample consisted of the following:

Thirty-six production operators (CNC, assembly, quality gate);

Twenty-four equipment maintenance technicians;

Thirty supply chain/logistics coordinators;

Eighteen R&D assistants supporting shop floor trials.

No exclusion criteria other than unwillingness to sign the consent form were required.

All participants provided written informed consent prior to the interview and were informed of their right to withdraw up to two weeks after data collection.

3.2. Data Collection

Data were collected between 1 July and 31 August 2025. A semi-structured interview guide (Table A1) was constructed around the TOE domains and pilot-tested with two volunteers. Questions were open, e.g., “What core digital technologies are adopted by your enterprise? What adaptation or conflict links exist between these technologies and production processes/equipment maintenance processes?” Interviews lasted 45–120 min (median = 82 min; total $\approx$ 150 h). All conversations were audio-recorded on encrypted devices and transcribed verbatim within 24 h under a confidentiality agreement.

Auxiliary materials were collected when available: (a) shift logs, (b) training PowerPoints, (c) quick-response cards, and (d) screen shots of dashboards. These documents were used only for triangulation and will not be publicly released because they contain firms’ proprietary parameters.

3.3. Analytical Procedure—Grounded Theory

Analysis followed the classic Straussian open–axial–selective coding sequence (X. M. Chen, 2000) using NVivo 12 Plus.

Step 1—Open coding: Two investigators independently line-coded the first five transcripts, allowing for concepts to emerge inductively. A start list of 36 first-order concepts was agreed upon. After independently line-coding the first five transcripts, the two researchers resolved discrepancies through a three-step process: (1) concept comparison—cross-checking the definition of 36 first-order concepts and marking 4 divergent points; (2) raw data retrieval—re-examining interview texts to align with the core semantics of respondents’ expressions; and (3) literature calibration—referencing the TOE framework’s dimensional definitions to classify controversial concepts. Additionally, to verify coding reliability, 20% of the interview texts (22 pieces) were randomly selected for inter-coder consistency testing using Cohen’s kappa coefficient, yielding a kappa value of 0.83 ($p < 0.001$), meeting the “high consistency” standard (Guest et al., 2006).

Step 2—Axial coding: Constant comparison grouped concepts into ten sub-categories. Memos captured contextual conditions, actions/interactions, and consequences.

Step 3—Selective coding: The core category “TOE matching spiral” was identified for its ability to integrate all sub-categories. Theoretical saturation was declared when three additional interviews produced no new properties (Guest et al., 2006).

3.4. Use of Generative AI

Generative AI was not used for text, data, or graphics generation, nor for study design, data collection, analysis, or interpretation.

4. Results

4.1. Open Coding

In open coding, researchers coded the collected data word by word, without missing any important information, until information saturation was reached. Additional data collection is required if new information is available. Researchers first decomposed the collected data, assigned concepts to it, and then recombined them in a new manner. X. M. Chen (2000) proposed that the main purpose of open coding is to conduct open exploration of the collected raw data, identify conceptual categories, name the categories, determine the attributes and dimensions of the categories, and then name and categorize research objects. In this study, 36 concepts and 10 categories were extracted using open coding, as shown in Appendix A.

4.2. Axial Coding

The focus of the researchers in this coding process was to identify and establish various connections between conceptual categories and present the organic relationships between different parts, including causal relationships, type relationships, and process relationships. In axial coding, researchers conducted an in-depth analysis of one category at a time and explored the relevant relationships within this category. Three main categories were obtained in the coding process, as listed in Table 1.

Table 1. Results of Axial Coding.

Main Categories	Sub-Categories	Connotation of Relationships
AA1 Manufacturing Digital Technology	A1 Industrial Infrastructure Construction	Hardware foundations built by enterprises for digital transformation, such as industrial internet platforms, intelligent production equipment (e.g., intelligent machine tools, robots), and industrial sensors.
	A2 Production Data Acquisition and Analysis	Collecting production progress, equipment operation, and product quality data through MES/ERP systems, and conducting abnormal early warning and efficiency analysis (e.g., statistics on equipment failure rates).
	A3 Flexible Production Platform Construction	Flexible production line systems built to meet customized needs (e.g., modular production platforms in the automotive industry) and cross-workshop production collaboration platforms.
	A4 Manufacturing Technology Innovation and Introduction	Introducing technologies such as digital twins (e.g., digital simulation for product R&D), additive manufacturing (3D printing), and industrial software (PLM product lifecycle management).

Table 1. *Cont.*

Main Categories	Sub-Categories	Connotation of Relationships
AA2 Manufacturing Organizational System	A5 Production Structure Adjustment	Reorganization of production teams to adapt to digital technology (e.g., “equipment maintenance + digital operation” hybrid teams) and cross-departmental collaboration structures (production–R&D–supply chain teams). Optimizing production processes (e.g., intelligent scheduling and digital quality traceability), equipment maintenance processes (e.g., predictive maintenance replacing regular maintenance), and supply chain collaboration processes (e.g., data sharing between upstream and downstream enterprises).
	A6 Manufacturing Process Optimization	Training/introducing digital talents such as industrial engineers (responsible for MES system operation), intelligent equipment maintenance personnel, and production data analysts.
	A7 Manufacturing Talent Training and Introduction	
AA3 Manufacturing Transformation Environment	A8 Supply Chain Ecosystem Integration	External supply chain collaboration environment faced by enterprises (e.g., industrial internet interconnection between upstream and downstream enterprises and supplier data sharing requirements) and digital cooperation in industrial clusters (e.g., collaboration in the automotive industrial cluster). Market competition (e.g., intensified customized customer demands and efficiency competition from peer smart factories) and supply chain cost pressure (e.g., digital collaboration requirements for global supply chains).
	A9 Manufacturing Competition Pressure	Customers’ personalized product demands (e.g., customized accessories in the electronics industry) and downstream enterprises’ demands for shorter delivery cycles (e.g., rapid response in the FMCG supply chain).
	A10 Manufacturing Demand Changes	

4.3. Selective Coding

The core category “TOE matching spiral” was identified through three-stage analysis: (1) category correlation analysis—using NVivo 12 Plus’s “category correlation matrix,” the chain correlation between “technological dimension (A1–A4)—organizational dimension (A5–A7)—environmental dimension (A8–A10)” was found to be the most frequent (98 times in total); (2) high-frequency narrative extraction—89% of respondents (96/108) mentioned that “technological implementation requires supporting organizational adjustments, which in turn need to respond to market/policy changes”; and (3) theoretical adaptability verification—this cyclic logic aligns with the TOE framework’s core view of “three-dimensional interaction” but breaks through the static perspective of existing research. Theoretical saturation was verified by stratified sampling: 3 additional respondents (covering underrepresented industries and positions) were interviewed, and no new concepts or categories emerged, meeting the standard (Guest et al., 2006).

The derivation of the core conclusion “frontline feedback moderates the TOE matching spiral” is as follows: (1) coding finding—70% of respondents (76/108) reported that “frontline opinions directly affect the adaptation effect of technology and organization”; (2) logic extraction—frontline employees correct mismatches between technology and organization

through “problem identification → internal transmission → plan adjustment”; and (3) theoretical integration—this moderating role is integrated into the TOE framework, forming a closed-loop spiral of “technology-driven → organization-adapted → environment-adjusted → frontline feedback → technology iteration.”

Taking “the technology–oxidation–environment-matching mechanism in enterprise digital transformation” as the core category, this study integrates other main categories and connects the core category with the main categories through an operation mechanism, constructing a new theoretical model. This model includes three parts—digital technology, enterprise organization, and transformation environment—as shown in Figure 1.

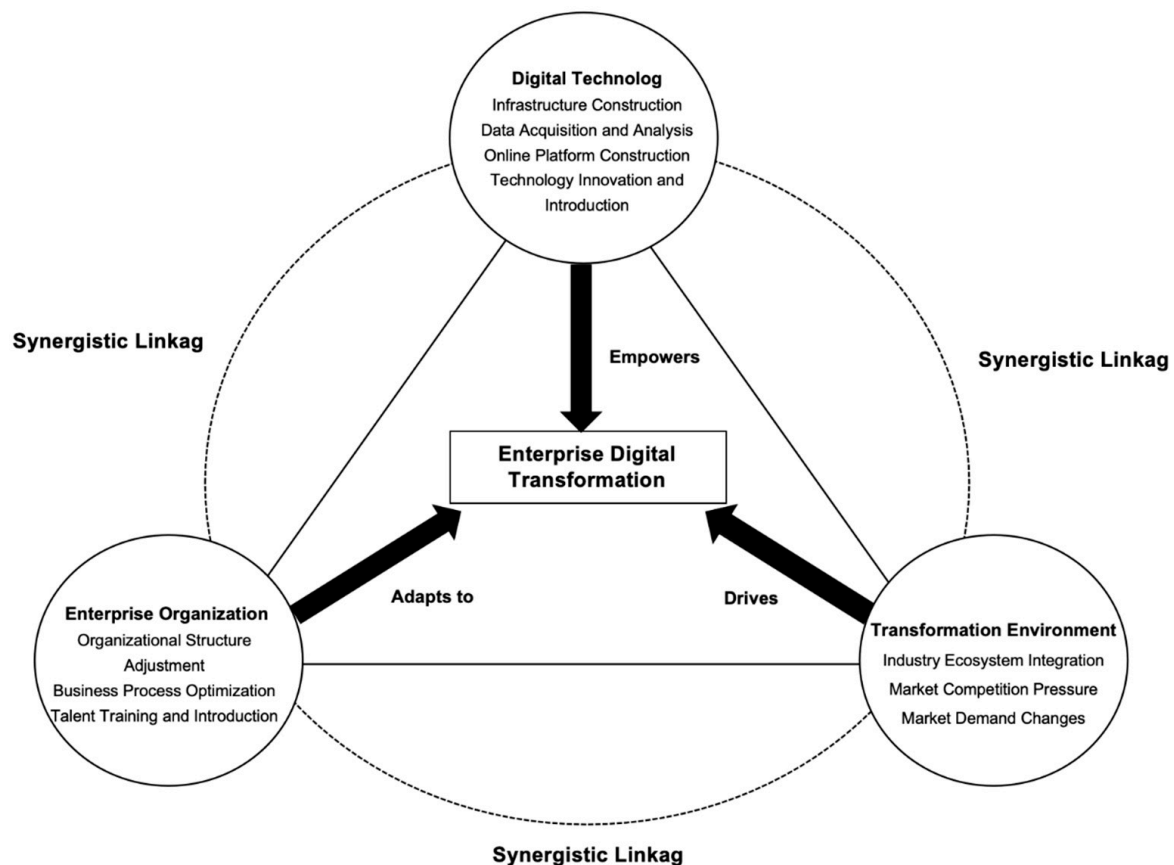


Figure 1. Theoretical Model of the TOE Matching Mechanism in Enterprise Digital Transformation.

This theoretical model explains the matching mechanism of the digital transformation of China’s manufacturing industry in three dimensions (technology, organization, and environment):

1. **Technology Dimension:** Industrial internet platforms are the cornerstone of manufacturing transformation but need to be coordinated with production equipment. Digital twin technology can shorten the product R&D cycle, but needs to be adapted to the processes of the R&D department; otherwise, simulation data cannot be applied to actual production.
2. **Organization Dimension:** Flexible production architecture can improve the response speed to customization, but departmental silos lead to the separation of production data and R&D data. The insufficient reserves of industrial engineers reduce the utilization rate of MES systems.
3. **Environment Dimension:** Customized customer demands drive the construction of flexible production lines, but the globalization of supply chains increases the difficulty of cross-regional data collaboration. Pilot policies for smart manufacturing

can accelerate the transformation of enterprises, but SMEs struggle to benefit from policy dividends because of insufficient funds.

The three dimensions form a spiral path of “manufacturing technology introduction → production organization adaptation → supply chain environment response”. Successful transformation relies on the closed loop of “top-level production strategy → frontline equipment feedback”. Owing to “insufficient funds for equipment transformation and weak supply chain bargaining power”, SMEs face the dual challenges of insufficient technology absorption and rising costs.

5. Discussion

Through a survey of frontline employees in manufacturing enterprises in the GBA, this study constructs a theoretical model of the “Technology–Organization–Environment”-matching mechanism using grounded theory, revealing the dynamic interactive relationship among technology, organization, and environment in the digital transformation of the manufacturing industry. From a micro perspective, this model expands the application scenarios of the TOE framework and provides a new theoretical perspective to understand the complex mechanism of digital transformation in manufacturing.

5.1. Analysis of Each Dimension

5.1.1. Technology Dimension

This study found that the construction of digital infrastructure is the cornerstone of transformation. However, the generation of value by technology depends highly on the matching of organizational capabilities. This finding echoes the notion that the application efficiency of AI systems decreases without coordination with training systems (Zuo et al., 2021). However, this study further clarifies the particularity of manufacturing: the adaptation relationship between technology and organization needs to focus on “on-site production collaboration” rather than general training.

5.1.2. Organization Dimension

The core of the organizational dimension lies in building dynamic capabilities. Establishing a digital department or digital team within the enterprise to participate in digital operations and information system development can effectively advance the company’s digital transformation. This demonstrates that an organizational structure capable of adapting to technological change is a key factor in digital transformation.

In terms of business process optimization, measures such as online approval and paperless offices have significantly reduced the operating costs. However, frontline employees also mentioned the problem of “difficult data sharing due to departmental silos,” reflecting that incomplete organizational restructuring may become an obstacle to transformation.

In terms of talent training and introduction, strengthening the reserve of technical talent and employee training can enhance willingness to adopt technology. However, some enterprises retain the problem of “emphasizing technology procurement while neglecting endogenous capability building,” which undermines the sustainability of the transformation. This is consistent with the theory of differentiated transformation paths—namely the resource-driven type and capability-driven type (Niu et al., 2024). However, this study further clarifies that the core collaborative model in manufacturing is the “three-dimensional linkage of production, R&D, and the supply chain.”

5.1.3. Environment Dimension

Market competition pressures and shifting environmental demands serve as external drivers for transformation. To meet customer requirements, some enterprises have invested

in building industrial internet platforms to enable real-time production data sharing. Despite increased costs, these companies have seen greater order volume growth. Conversely, small and medium-sized suppliers unable to connect to such platforms have been excluded from supply chains. This highlights the moderating role of environmental dynamics in technology–organizational alignment, and matches the view that SMEs’ transformation relies on external traction (Zhang et al., 2022). However, this study further points out that “cross-regional data collaboration” is the core pinch point of environmental adaptation.

5.2. Dynamic Matching of the Three Dimensions

The dynamic matching of technology, organization, and environment presents a spiral evolution characteristic. The study found that successful transformation cases often experience a cycle of optimization: “technology introduction → organization adaptation → environment response”.

However, small and micro manufacturing enterprises often face the dual dilemmas of insufficient technology absorption and rising costs due to their weak resource integration capabilities.

5.3. Practical Implications

This study has a multidimensional guiding value for the practice of digital transformation in manufacturing.

5.3.1. For Manufacturing Enterprise Management

Avoid blind procurement of intelligent equipment; prioritize the promotion of “equipment networking → data interconnection → process adaptation”. For example, small and medium-sized machinery enterprises can monitor equipment networking before introducing MES systems. Establish a “frontline equipment feedback mechanism” and incorporate operator problems with equipment use into the technology optimization process. For example, feedback from equipment maintenance personnel can be collected monthly to adjust the predictive maintenance model accordingly.

5.3.2. For Regional Policies

The GBA needs to establish a commercial cross-city manufacturing industrial internet platform; unify data standards for industries such as automobiles and electronics; and implement information sharing. Launch “equipment transformation subsidies + talent training vouchers” for SMEs to reduce transformation costs.

5.3.3. For Small and Medium-Sized Manufacturing Enterprises

Focus on digitalization in segmented scenarios and reducing the cost of independent transformation through industrial cluster cooperation. Prioritize connections with the supply chains of core customers to drive transformation through market demand.

5.3.4. For Industry Ecosystem

Promote cooperation among “manufacturing enterprises, industrial software vendors, and universities” to solve the “bottleneck” problem of industrial software. Industry associations should formulate digital standards for the manufacturing industry to avoid repeated investment by enterprises.

5.4. Theoretical Contributions

1. Expanding the application level of the TOE framework: Existing TOE research mostly focuses on the firm or strategic business unit level, while this study extends the framework from “macro strategic adaptation” to “micro practical implementation” by

exploring frontline employees' perspectives, supplementing the "mediating role of frontline employees as technology carriers.

2. Breaking the static cognition of the TOE framework: This study proposes a dynamic spiral model of "technology introduction → organization adaptation → environment response → frontline feedback → technology iteration," explaining the heterogeneous adaptation logic under regional heterogeneity and enterprise size differences.
3. Filling the empirical gap in manufacturing digital transformation: Based on first-hand narratives from frontline employees, this study identifies grass-roots-specific adaptation barriers and provides empirical evidence for subsequent research.

5.5. Research Limitations and Future Prospects

Although this study provides new theoretical insights into the digital transformation of the manufacturing industry, it has the below limitations.

5.5.1. Limitations of Sample Scope

1. This study focuses on GBA. Although the region is a manufacturing hub, manufacturing enterprises of varying scales exhibit heterogeneous characteristics and the industry is dominated by the manufacture of automobiles and electronics. The generalizability of the conclusions to process manufacturing industries must be verified.
2. The policy environment and market structure of the GBA are specific, so the generalizability of the research conclusions to manufacturing industries in the central and western regions or areas beyond the GBA needs further verification.

Future research can adopt a "stratified comparison design": (1) compare process manufacturing with discrete manufacturing to analyze the impact of production continuity on the TOE matching mechanism; (2) compare the GBA with manufacturing bases in central and western China to explore the moderating effect of digital infrastructure levels; and (3) focus on micro-enterprises to analyze their TOE adaptation strategies under extreme resource shortages.

5.5.2. Limitations of Dynamic Research

1. Digital transformation is a continuous, evolutionary process. This study only conducted interviews from July to August 2025, which lacked long-term tracking of the transformation effects.
2. This study did not consider the "collaboration between production safety and digitalization" in the manufacturing industry. Future research could supplement this dimension.

Addressing the aforementioned limitations, future research can advance in two aspects: (1) conduct a two-wave (1-year and 3-year) longitudinal tracking study on sample enterprises to collect quantitative indicators such as technology application rate and organizational adjustment frequency, so as to analyze the phased characteristics of the TOE matching spiral and the long-term impact of frontline feedback; and (2) incorporate the dimension of "collaboration between production safety and digitalization" to explore the adaptation mechanism of intelligent monitoring systems, safety process optimization, and safety production policies. Additionally, quantitative research can be conducted to verify the model's generalizability, measure TOE matching degree and frontline feedback, collect paired samples from frontline employees and middle managers, and use structural equation modeling (SEM) to test causal relationships.

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R.L.; project administration, D.H. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: This study has obtained ethical review exemption from the School of Management, Jinan University, with the specific reasons as follows: First, the research is a low-risk social science interview study focusing on the TOE fit mechanism in the digital transformation of manufacturing, which does not involve life sciences or medical fields. The interview topics revolve around non-sensitive work-related content and will not cause physical or mental harm to participants; Second, all research data are anonymized throughout the process without recording identifiable information, and the research purpose is purely academic exploration without commercial interest orientation, so there is no risk of leakage of sensitive information or commercial interests; Third, the research adopts the semi-structured interview method, which falls under the exemption category of "interview and survey research" stipulated in Article 32 of the Measures for the Ethical Review of Human-Related Life Science and Medical Research (2023 Edition), and basic ethical requirements such as informed consent and data confidentiality have been strictly implemented; Fourth, the research is classified as minimal risk, which complies with the core condition for exemption from review specified in the Measures for the Ethical Review of Science and Technology (Trial Implementation).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The complete audio files cannot be shared as they contain personally identifiable information and company confidential data. The organized data is presented in the tables within the paper.

Acknowledgments: During the preparation of this manuscript/study, the authors used Grammarly for the purposes of superficial English proofreading. The authors have reviewed and edited the output and take full responsibility for the content of this publication.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Appendix A.1

Table A1. Interview Outline.

No.	Questions
1	What core digital technologies (e.g., intelligent machine tools, MES systems, industrial robots) are adopted by your enterprise? What adaptation or conflict links exist between these technologies and production processes/equipment maintenance processes (e.g., intelligent machine tools not matching existing processes)?
2	To support digital transformation, what adjustments has the enterprise made at the organizational level (e.g., reorganization of production teams, addition of digital positions in the equipment maintenance team, cross-departmental collaboration teams)? How do these adjustments interact with the application of intelligent equipment/industrial internet (e.g., whether the reorganization of production teams improves equipment utilization)?
3	How do GBA manufacturing policies (e.g., smart manufacturing subsidies, industrial internet pilots) and market competition (e.g., customized customer demands, digital requirements from upstream and downstream of the supply chain) affect the enterprise's transformation decisions? How does the enterprise select adaptive technologies based on these environmental factors (e.g., introducing flexible production lines to meet customized demands)?
4	During the transformation, what contradictions (e.g., separation of MES system data and supply chain data) or synergy effects (e.g., adaptation of industrial robots and production processes to improve efficiency) have you observed among the application of intelligent equipment, adjustment of production processes, and supply chain demands? What measures has the enterprise taken to promote the matching of the three?
5	From the frontline perspective, what deficiencies still exist in the enterprise's digital transformation in terms of intelligent equipment application, production organization management, and adaptation to the supply chain environment (e.g., insufficient equipment training, disconnected cross-departmental data)? What suggestions are there for optimizing the matching mechanism of the three in the future?

Appendix A.2

Table A2. Results of Open Coding.

Excerpts from Raw Statements	Conceptualization	Categorization
"Our workshop added 5 intelligent machining centers last year and built a workshop-level industrial internet platform. Now the equipment startup rate can be monitored in real time, but the data interface between the platform and old equipment is incompatible, so data from some machine tools cannot be uploaded."	aa1 Deployment of intelligent machining centers + construction of workshop-level industrial internet platform + incompatible data interfaces between new and old equipment	A1 Industrial Infrastructure Construction
"To monitor the energy consumption of the production line, the factory installed intelligent sensors on injection molding machines and stamping machines, which can collect real-time current and temperature data. However, sometimes the sensor calibration is inaccurate, leading to large deviations in energy consumption data."	aa2 Installation of intelligent sensors (for energy consumption monitoring) + collection of equipment operation data + data deviation caused by inaccurate sensor calibration	A1 Industrial Infrastructure Construction
"A supply chain partner required us to connect to their industrial internet platform. Now our component production data can be synchronized to Huawei in real time, but the annual platform fee is 80,000 yuan, which is a high cost for small and medium-sized factories like us."	aa3 Connection to customer's industrial internet platform + real-time synchronization of component production data + high platform usage cost	A1 Industrial Infrastructure Construction
"After using the MES system, I can check the processing time and production qualification rate of the machine tools I am responsible for as soon as I turn on the system at work. If defective products appear, the system will automatically mark which process is problematic and push early warning information."	aa4 Application of MES system + query of processing time/qualification rate data + location of defective product processes + automatic early warning push	A2 Production Data Acquisition and Analysis
"The equipment maintenance team now checks the equipment operation data in the ERP system every day, such as spindle speed fluctuations and lubricating oil level. If the data exceeds the threshold, maintenance is arranged in advance, unlike before when maintenance was only done after equipment failure."	aa5 Query of equipment data in ERP system + monitoring of spindle speed/lubricating oil level + advance maintenance for threshold exceeding	A2 Production Data Acquisition and Analysis
"Visual inspection equipment is now used in the quality inspection link. Inspection data is directly synchronized to the quality database. After connecting with the MES system, the inspection time and inspector of each product can be traced, and defective products cannot flow to the next process at all."	aa6 Application of visual inspection equipment + synchronization of quality data to database + tracing of defective products via MES system	A2 Production Data Acquisition and Analysis
"To meet customers' small-batch orders, we transformed the production line into a modular one. For example, when assembling mobile phone accessories, we can switch to producing different models by changing the fixture, which is 3 h faster than changing the entire production line before."	aa7 Transformation of modular production lines + rapid switching of multi-model products + reduction in production change time	A3 Flexible Production Platform Construction

Table A2. Cont.

Excerpts from Raw Statements	Conceptualization	Categorization
“The factory has built a cross-workshop flexible production collaboration platform. For example, components from the Shenzhen branch can be deployed to the Guangzhou assembly workshop in real time. Last month, a customer needed 1000 customized routers, and we completed the production in 3 days relying on this platform.”	aa8 Construction of cross-workshop flexible production collaboration platform + cross-regional component deployment + rapid delivery of customized products	A3 Flexible Production Platform Construction
“For the multi-batch production of auto parts, we set up an order priority function on the platform. Urgent orders can be automatically prioritized without manual adjustment of the production plan, avoiding delays in delivery.”	aa9 Setting of order priority in flexible production platform + automatic prioritization of urgent orders + no manual adjustment of production plan	A3 Flexible Production Platform Construction
“The R&D department uses digital twin technology for the simulation of auto parts, such as the stress test of engine cylinder blocks. There is no need to make physical prototypes, the R&D cycle is shortened from 2 months to 25 days, and material costs are reduced by 40%.”	aa10 Application of digital twin technology (component simulation) + shortening of R&D cycle + reduction in material costs	A4 Manufacturing Technology Innovation and Introduction
“3D printing equipment was introduced last year to produce small-batch customized molds. For example, when a customer needs home appliance molds of special specifications, it used to take 2 weeks to make the mold, but now it can be printed in 3 days, and the design can be modified.”	aa11 Introduction of 3D printing equipment + rapid production of customized molds + convenient design modification	A4 Manufacturing Technology Innovation and Introduction
“The PLM product lifecycle management software was launched. All data from product design, trial production to mass production is stored in it. The R&D and production departments can share a set of data, unlike before when each department stored its own data, which often led to data inconsistency.”	aa12 Launch of PLM software + integration of product lifecycle data + data collaboration between R&D and production	A4 Manufacturing Technology Innovation and Introduction
“We transformed the original ‘operator team’ into a ‘hybrid team of operators + equipment maintenance personnel + data analysts’. For example, when data anomalies occur during production, analysts can check the cause on the spot without having to contact other departments.”	aa13 Formation of hybrid production teams (operators + maintenance personnel + analysts) + on-site troubleshooting of data anomalies	A5 Production Structure Adjustment
“The factory established a cross-departmental team of ‘production-R&D-supply chain’ specifically for digital transformation. For example, the plan for the new flexible production line was formulated by this team, which is much faster than the previous promotion by a single department.”	aa14 Establishment of cross-departmental collaboration team (production-R&D-supply chain) + formulation of flexible production line plan	A5 Production Structure Adjustment
“The equipment department added a ‘digital maintenance position’ specifically responsible for the software debugging of intelligent equipment, such as the CNC system of machine tools and the fault diagnosis of industrial internet platforms. Previously, these tasks were outsourced to manufacturers.”	aa15 Establishment of digital maintenance positions + software debugging of intelligent equipment + internal undertaking of outsourced work	A5 Production Structure Adjustment

Table A2. Cont.

Excerpts from Raw Statements	Conceptualization	Categorization
“After using the intelligent scheduling system, the production plan can be automatically arranged according to the order quantity and equipment capacity. For example, there are 5000 air-conditioning accessory orders this month, and the system assigns production to 3 lines, which saves 2 h compared with manual scheduling and avoids missed orders.”	aa16 Application of intelligent scheduling system + matching of order and equipment capacity + reduction in scheduling time + avoidance of missed orders	A6 Manufacturing Process Optimization
“Equipment maintenance has been changed from ‘regular maintenance’ to ‘predictive maintenance’. The system analyzes equipment operation data, such as motor vibration frequency, to predict faults in advance. Last year, the equipment downtime was reduced by 35% compared with the previous year.”	aa17 Replacement of regular maintenance with predictive maintenance + fault prediction based on equipment operation data + reduction in downtime	A6 Manufacturing Process Optimization
“Now RFID scanning is used for the warehousing of components, eliminating the need for manual counting. Data is directly synchronized to the warehouse management system. After connecting with the production workshop, the system automatically issues an early warning when materials are insufficient, unlike before when shortages were only discovered when the workshop requested materials.”	aa18 RFID scanning for component warehousing + data synchronization to warehouse management system + automatic early warning for material shortage	A6 Manufacturing Process Optimization
“This year, 8 industrial engineers were recruited specifically responsible for the connection between the MES system and intelligent equipment. We were also sent to the training base of a communication company to learn intelligent machine tool operation. Now 80% of the people in the workshop can use data analysis tools.”	aa19 Recruitment of industrial engineers + training on intelligent machine tool operation + mastery of data analysis tools by employees	A7 Manufacturing Talent Training and Introduction
“Digital training is conducted every quarter. For example, we learned the basic operation of digital twins last month and supply chain data collaboration this month. Only those who pass the exam can take up their posts. Now we maintenance personnel can also understand the data analysis reports of equipment.”	aa20 Quarterly digital training (digital twins + supply chain collaboration) + post-qualification-through-training assessment + improvement of data analysis capabilities of maintenance personnel	A7 Manufacturing Talent Training and Introduction
“The factory cooperated with a university to set up an ‘intelligent manufacturing class’ to cultivate production data analysts in a targeted manner. 12 students have graduated so far, and they are now responsible for analyzing the production efficiency of the workshop and can also put forward suggestions for improvement plans.”	aa21 University–enterprise cooperative intelligent manufacturing class (targeted cultivation of data analysts) + analysis of production efficiency + suggestions for improvement plans	A7 Manufacturing Talent Training and Introduction
“We have connected data with 3 component suppliers in Foshan. Now we can check their delivery progress and raw material quality data in real time. Last month, a batch of aluminum materials was unqualified, and we replaced the supplier in advance without delaying production.”	aa22 Data interconnection with suppliers + real-time query of delivery progress/raw material quality + timely replacement of unqualified suppliers	A8 Supply Chain Ecosystem Integration

Table A2. Cont.

Excerpts from Raw Statements	Conceptualization	Categorization
“We joined the digital platform of the Guangzhou automotive industrial cluster, which allows us to share capacity data with leading enterprises such as GAC and Dongfeng. For example, when we have surplus capacity, we can undertake temporary orders from leading enterprises, and we earned an additional 2 million yuan last year through this.”	aa23 Joining the digital platform of the industrial cluster + sharing of capacity data with leading enterprises + undertaking temporary orders with surplus capacity	A8 Supply Chain Ecosystem Integration
“Blockchain technology is used to synchronize order data with cross-border suppliers, such as rubber suppliers in Southeast Asia. Now they can see our needs in real time, the delivery cycle has been shortened from 45 days to 30 days, and the source of raw materials can also be traced.”	aa24 Application of blockchain technology (order synchronization with cross-border suppliers) + shortening of delivery cycle + traceability of raw material sources	A8 Supply Chain Ecosystem Integration
“The machinery factory next door built a smart factory last year, with production efficiency 20% higher than ours. Now customers all require us to use intelligent equipment, otherwise they will not sign long-term contracts. We have to increase digital investment this year.”	aa25 Competition from peer smart factories + customer requirements for intelligent equipment application + increase in digital investment	A9 Manufacturing Competition Pressure
“Apple requires all our production lines to meet the ‘lighthouse factory’ standards next year, such as an automation rate of over 90% and 100% data transparency. If we fail to meet these standards, our qualification as a supplier will be revoked.”	aa26 Customer (Apple) requirements for lighthouse factory standards (automation rate + data transparency) + pressure on supplier qualification	A9 Manufacturing Competition Pressure
“Electronic factories in Shenzhen now all use AI visual inspection, which is 3 times faster than manual inspection and has a lower defect rate. If we do not keep up, we will lose small-order customers in the future.”	aa27 Application of AI visual inspection by peers (efficiency + quality advantages) + pressure of losing small-order customers	A9 Manufacturing Competition Pressure
“Among the orders Xiaomi gave us this year, 30% are customized mobile phone charging accessories, which require printing the customer’s logo and adjusting the interface specifications. We have to modify the production line to meet these requirements.”	aa28 Orders for customized mobile phone charging accessories (logo + interface adjustment) + modification of production line for adaptation	A10 Manufacturing Demand Changes
“FMCG customers now require the delivery cycle to be shortened from 15 days to 7 days. For example, for laundry detergent packaging bottles, we used to produce in batches, but now we have to use flexible lines for small-batch and rapid production, otherwise we cannot keep up with their distribution schedule.”	aa29 FMCG customer requirements for shorter delivery cycles + small-batch and rapid production via flexible lines	A10 Manufacturing Demand Changes
“Automotive customers recently requested in-vehicle displays that are not only thin but also support wireless charging. We have to use new injection molding processes and modify the product design, otherwise we cannot meet their new needs.”	aa30 Customized requirements for in-vehicle displays (thin design + wireless charging) + improvement of injection molding processes + modification of product design	A10 Manufacturing Demand Changes

Table A2. Cont.

Excerpts from Raw Statements	Conceptualization	Categorization
“We produce accessories for a home appliance enterprise. They require each accessory to have a unique traceability code, which can be used to check the production time, quality inspector, and raw material batch. They said this is to respond to consumers’ quality complaints, so we have to upgrade the traceability system.”	aa31 Requirements for unique accessory traceability codes (production/quality inspection/raw material traceability) + upgrade of traceability system	A10 Manufacturing Demand Changes
“Last month, the workshop’s industrial internet platform was connected to the municipal power monitoring system, enabling us to arrange production to avoid peak electricity consumption. For example, we prioritize assembly work during the day when electricity prices are high, and start machine tool processing at night when electricity prices are low, saving 12,000 yuan in electricity costs per month.”	aa32 Connection of industrial internet platform to municipal power system + production arrangement to avoid peak hours + Reduction in electricity costs	A1 Industrial Infrastructure Construction
“Digital twin technology is used to optimize the production line layout. For example, the distance between the assembly line and the inspection line was shortened by 2 m, reducing the material transportation time by 1.5 h per day. It can also simulate the space occupation after adding new equipment without on-site trial installation.”	aa33 Application of digital twin technology (production line layout optimization) + reduction in material transportation time + simulation of equipment layout	A4 Manufacturing Technology Innovation and Introduction
“The production department and supply chain department now share a collaboration platform. When materials are insufficient in production, the system automatically sends a replenishment reminder to suppliers, so we don’t have to call to urge them. Last month, 200 bearings were insufficient, and the supplier delivered them in 3 days.”	aa34 Application of production-supply chain collaboration platform + automatic replenishment reminder for material shortage + improvement in supplier response speed	A8 Supply Chain Ecosystem Integration
“The factory sent us to take industrial engineer courses, mainly learning advanced functions of the MES system, such as data modeling to analyze production bottlenecks. Now I can find the stuck workstations in the assembly line through system data and put forward improvement plans.”	aa35 Training on industrial engineer courses (advanced MES functions) + data modeling analysis of production bottlenecks + proposal of improvement plans	A7 Manufacturing Talent Training and Introduction
“To cope with multi-variety production, we transformed the machine tool fixtures into quick-change ones. Combined with the flexible production platform, we can now change the fixture in 15 min without disassembling the entire fixture, which is 1 h faster than before.”	aa36 Transformation of quick-change fixtures + adaptation to flexible production platform + reduction in production change time	A3 Flexible Production Platform Construction

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