Configurational Pathways of Manufacturing Servitization Transformation in the Digital Economy Context

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Abstract. Manufacturing servitization is crucial for high-quality manufacturing development. Based on the TOE framework, this study uses dynamic QCA to identify configurations driving high servitization among service-oriented manufacturing enterprises. The results show that no single factor is necessary for high-level servitization; two paths, namely digital capability-driven and innovation talent-supported paths, can achieve high-level servitization, both relying on R&D intensity and employee digital capability. The identified configurations remain stable across time, regions, and industry contexts.

Keywords: digital economy; manufacturing servitization; dynamic QCA; configurations

1 Introduction

The digital economy has become a key driver of high-quality economic development by fostering innovation and transforming traditional industries. With increasing competition and diversified customer demands, manufacturing enterprises can no longer rely solely on product-based advantages and need to enhance value creation through servitization, digital empowerment, and business model transformation. Therefore, identifying the driving mechanisms and pathways of manufacturing servitization is critical for industrial upgrading. However, servitization transformation is a complex process shaped by interactions among technological, organizational, and environmental factors. This study adopts the TOE framework and dynamic QCA to identify configurational pathways through which multiple factors jointly facilitate manufacturing servitization.

This study makes two contributions. First, it advances beyond single-factor explanations by adopting a configurational perspective to uncover the complex causal mechanisms of manufacturing servitization. Second, it integrates the digital economy context and examines the role of emerging digital technologies in facilitating servitization transformation, thereby extending research on manufacturing upgrading.

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2 Literature Review and Theoretical Analysis

The digital economy is reshaping manufacturing production and value creation. Existing studies show that digital development promotes technological innovation, resource efficiency, and manufacturing servitization (Seclen-Luna et al., 2025). Digital technologies also enhance industrial integration and supply chain coordination, facilitating manufacturing transformation (Le-Dain et al., 2023). Previous research has explored internal and external drivers of servitization, including digital technology adoption, innovation capability, competitive pressure, government support, and institutional environments (Zhang et al., 2024). However, two gaps remain: existing studies mainly focus on individual effects while overlooking interactions among technological, organizational, and environmental factors, and the configurational mechanisms through which different factors jointly drive servitization across contexts remain underexplored. This study addresses these gaps by adopting a configurational perspective to examine the multiple pathways of manufacturing servitization.

The TOE framework suggests that organizational transformation is shaped by technological, organizational, and environmental factors. Based on this perspective, this study selects six conditions to explain manufacturing servitization. Technological factors include digital-intelligent technology and R&D intensity, which support information processing and continuous innovation (Yu et al., 2025). Organizational factors include employee digital capability and digital infrastructure, reflecting firms' technology adoption and data-driven coordination capabilities (Kang et al., 2026). Environmental factors include provincial informatization level and industry competition, representing external digital support and competitive pressures (Wang et al., 2025). Accordingly, this study develops a TOE-based configurational model, suggesting that servitization emerges from the interaction of multiple conditions rather than a single driver. The research framework is shown in Figure 1.

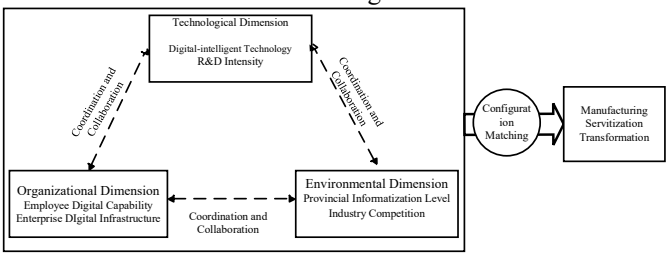


Fig. 1. Research framework

3 Research Design

3.1 Research Method

This study applies dynamic QCA to identify configurational pathways of manufacturing servitization. Unlike regression methods focusing on net effects, QCA captures how multiple conditions jointly generate outcomes and dynamic QCA further examines their

stability over time. Based on service-oriented manufacturing enterprises announced by the Ministry of Industry and Information Technology from 2017 to 2024, this study obtains 504 observations from the CSMAR and CNRDS databases.

3.2 Variable Measurement and Calibration

(1) Outcome Variable.

Manufacturing servitization transformation. Following Zhao et al.(2024), this study measures servitization using service-related input. Specifically, it is calculated as the ratio of the sum of R&D, selling, administrative, and financial expenses to operating revenue. Although this measure includes multiple expense categories, these inputs jointly reflect the resources invested by firms in service-oriented transformation. Therefore, this indicator captures firms' servitization transformation input intensity rather than merely accounting costs.

(2) Conditional Variables.

Digital-intelligent technology. Following Liu et al. (2026), this study uses text analysis to measure digital technology adoption based on the frequency of related keywords in annual reports, with logarithmic transformation； R&D intensity. Following Gao and Cui (2026), R&D intensity is measured as R&D expenditure divided by operating revenue； Employee digital capability. Following Guo and Zheng (2025), this study uses the proportion of employees with bachelor's degrees or above to represent digital talent capability； Enterprise digital infrastructure. Following Shen and Chang (2026), digital infrastructure is measured by the ratio of digital technology-related intangible assets to total intangible assets； Provincial informatization level. Following Zhang et al. (2026), this study uses the logarithm of mobile internet users to represent the regional digital environment； Industry competition. Following Du and Sun (2025), industry competition is measured by the Lerner index and positively adjusted.

Variable descriptions are presented in Table 1.

Table 1. Variable descriptions

Variable Type	Variable Name	Measurement
Outcome Variable	Manufacturing servitization transformation	(R&D expenses + selling expenses + administrative expenses + financial expenses) / operating revenue
Conditional Variables	Digital-intelligent technology	ln(frequency of digital transformation-related keywords in annual reports+1)
	R&D intensity	R&D expenditure / operating revenue
	Employee digital capability	Number of employees with bachelor's degree or above / total employees
	Enterprise digital infrastructure	Digital technology-related intangible assets / total intangible assets
	Provincial informatization level	ln(number of mobile Internet users)
	Industry Competition	1−Lerner index

(3) Variable Calibration.

This study applies direct calibration, setting the three anchors of full membership, crossover point, and full non-membership at 0.75, 0.50, and 0.25, respectively. The crossover point is adjusted to 0.501 to avoid bias caused by cases located at the threshold. Calibration information and descriptive statistics are presented in Table 2.

Table 2. Calibration information and descriptive statistics

Variable Name		Calibration		
		Full Membership	Crossover Point	Full Non-Membership
Outcome Variable	Manufacturing servitization transformation	0.2506	0.1851	0.1277
Conditional Variable	Digital-intelligent technology	3.2189	2.1972	1.0986
	R&D intensity	0.0587	0.0444	0.0336
	Employee digital capability	0.4337	0.2578	0.1777
	Enterprise digital infrastructure	0.0954	0.0468	0.0186
	Provincial informatization level	9.0768	8.8604	8.2926
	Industry Competition	0.8973	0.8833	0.8451

4 Results

4.1 Necessary Condition Analysis

Table 3. Necessary condition analysis based on dynamic QCA

Conditional Variable	High-level Servitization Transformation				Non-High-level Servitization Transformation			
	Summary Consistency	Summary Coverage	BCAD	WCAD	Summary Consistency	Summary Coverage	BCAD	WCAD
Digital-intelligent technology	0.616	0.605	0.1006	0.5485	0.483	0.487	0.1308	0.1331
~Digital-intelligent technology	0.478	0.475	0.1610	0.6468	0.608	0.618	0.1442	0.1113
R&D intensity	0.756	0.641	0.0268	0.3111	0.562	0.488	0.0671	0.1607
~ R&D intensity	0.396	0.469	0.0738	0.6632	0.586	0.711	0.1174	0.0980
Employee digital capability	0.610	0.610	0.1140	0.6304	0.456	0.468	0.1006	0.1396
~ Employee digital capability	0.468	0.457	0.1543	0.6959	0.619	0.619	0.0805	0.1020
Enterprise digital infrastructure	0.571	0.573	0.1543	0.5649	0.501	0.515	0.1476	0.1310
~ Enterprise digital infrastructure	0.516	0.503	0.1878	0.5895	0.585	0.583	0.1476	0.1272
Provincial informatization level	0.529	0.508	0.1174	0.6877	0.579	0.570	0.0839	0.1120
~ Provincial informatization level	0.552	0.562	0.1509	0.6140	0.500	0.521	0.1677	0.1352
Industry Competition	0.487	0.472	0.3086	0.5649	0.623	0.618	0.2885	0.1080
~Industry Competition	0.606	0.611	0.2784	0.5731	0.468	0.483	0.4193	0.1256

Note: BCAD stands for between-consistency Adjustment Distance, WCAD stands for within-consistency Adjustment Distance.

Table 3 shows that the consistency scores of all conditions are below 0.9, indicating that no single factor is necessary for achieving high servitization. Therefore, manufacturing servitization depends on the combination of technological, organizational, and environmental conditions rather than a single determinant.

4.2 Configurational Analysis of Sufficiency

Table 4. The configurational results of manufacturing servitization transformation

Conditional Variable	High-level Servitization Transformation		
	S1		S2
	S1a	S1b	S2
Digital-intelligent technology	●	●	
R&D intensity	●	●	•
Employee digital capability	•		●
Enterprise digital infrastructure	●	●	⊗
Provincial informatization level		⊗	⊗
Industry Competition	⊗	⊗	⊗
Consistency	0.824	0.834	0.852
PRI Consistency	0.754	0.755	0.804
Coverage	0.179	0.166	0.148
Unique Coverage	0.055	0.043	0.088
BCAD	0.0738	0.0771	0.0805
WCAD	0.3357	0.3521	0.3357
Overall Consistency	0.830		
Overall PRI Consistency	0.773		
Overall Coverage	0.310		

Note: ●indicates the presence of a core condition;⊗ indicates the absence of a core condition; • indicates the presence of a peripheral condition;⊗ indicates the absence of a peripheral condition; blank cells indicate that the condition may be either present or absent. The same applies below.

The raw consistency threshold was set at 0.8, with a case frequency threshold of 5 and a PRI consistency threshold of 0.70. The smaller BCAD and WCAD values indicate higher stability of the solution across time and cases. In this study, the WCAD value exceeding 0.2 suggests certain regional differences in the applicability of configurations. The configurational results of manufacturing servitization are presented in Table 4. Two main pathways are identified. The first is the digital capability-driven path (S1a and S1b), characterized by the combination of digital technologies, R&D intensity, and digital infrastructure. These configurations highlight the importance of internal digital capabilities in supporting servitization through service innovation, organizational coordination, and continuous improvement. The difference is that S1a includes employee digital capability as an auxiliary condition, whereas S1b achieves high servitization without it, suggesting that technological investment can partially compensate for limited digital talent. Kehua Data Co., Ltd. represents this path by integrating digital technologies, R&D innovation, and digital infrastructure through its “AI + Digital Energy”

strategy. The second is the innovation talent-supported path (S2), which relies on employee digital capability and R&D intensity. This configuration demonstrates that firms can achieve servitization through internal capabilities, with digital talent facilitating knowledge integration and organizational adaptation, and R&D enabling continuous service innovation. Chutian Technology Co., Ltd. reflects this pathway by leveraging R&D talent and technological innovation to enhance product intelligence and service capabilities.

(1) Analysis of Between-consistency.

Between-group consistency reflects the temporal stability of configurations in generating high servitization. As shown in Figure 2, S1a, S1b, and S2 all maintain consistency scores above 0.70 from 2017 to 2024, indicating strong stability over time. Although consistency declined during 2017–2021, all paths recovered afterward. S2 exhibited the strongest recovery and peaked in 2023, while S1a and S1b remained relatively stable, suggesting heterogeneous adaptation among different servitization pathways.

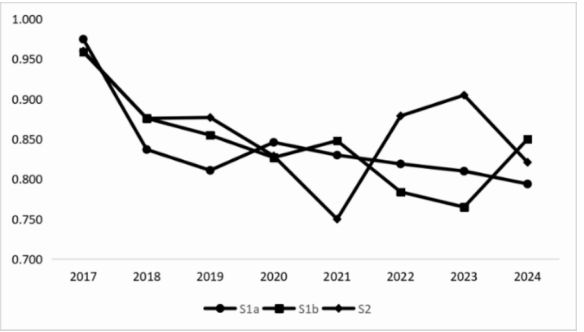


Fig. 2. Between-consistency analysis of high-level servitization transformation

(2) Analysis of Within-consistency.

Table 5 shows that all three configurations achieve regional consistency scores above 0.70, confirming their robustness across regions. In the eastern region, S1a exhibits the highest consistency, highlighting the role of digital infrastructure advantages. In contrast, S2 performs better in the central and western regions, suggesting that digital talent and R&D capabilities can compensate for limited digital resources. Overall, regional conditions influence the suitability of different servitization paths.

Table 5. Consistency levels of manufacturing enterprises in different regions

	S1a	S1b	S2
Eastern Region	0.873	0.854	0.842
Central Region	0.709	0.744	0.786
Western Region	0.849	0.849	0.874

4.3 Analysis of Industry Heterogeneity

As shown in Table 6, considering industrial heterogeneity, this study divides the sample into light- and heavy-industry groups. The results show that both groups exhibit similar configurational mechanisms, while light-industry firms present more diverse servitization pathways and rely more on external environmental support.

Table 6. Configurational analysis of manufacturing servitization transformation based on industry heterogeneity

Conditional Variable	light-industry				heavy-industry	
	L1	L2	L3	L4	H1	H2
Digital-intelligent technology	●	●	●	●	●	●
R&D intensity	●	●	●	●	●	●
Employee digital capability	●	●	●		●	●
Enterprise digital infrastructure		●		●	⊗	⊗
Provincial informatization level		●	⊗	⊗	⊗	
Industry Competition	⊗		⊗	⊗		⊗
Consistency	0.889	0.906	0.903	0.899	0.845	0.929
PRI Consistency	0.852	0.869	0.857	0.863	0.764	0.903
Coverage	0.233	0.143	0.162	0.125	0.131	0.18
Unique Coverage	0.024	0.047	0.043	0.028	0.03	0.084
BCAD	0.5899	0.2403	0.2767	0.3132	0.2180	0.0839
WCAD	0.1567	0.1326	0.1527	0.1728	0.3256	0.3537
Overall Consistency	0.892				0.867	
Overall PRI Consistency	0.864				0.862	
Overall Coverage	0.414				0.412	

4.4 Comparison Between Static and Dynamic QCA

Table 7. Configurational Pathways Identified by Static QCA

Conditional Variable	S1 '	S2 '	S3 '	S4 '
Digital-intelligent technology	●		●	●
R&D intensity		●	●	●
Employee digital capability	●	●	●	⊗
Enterprise digital infrastructure	⊗		⊗	●
Provincial informatization level	⊗	⊗		⊗
Industry Competition	⊗	⊗		⊗
Raw Unique	0.1232	0.1502	0.1427	0.0722
Unique Coverage	0.0275	0.0699	0.0470	0.0289
consistency	0.9172	0.8870	0.8653	0.9776
solution coverage	0.281			
solution consistency	0.887			

As shown in Table 7, a static fsQCA analysis using 2024 cross-sectional data was conducted to examine the robustness of the dynamic QCA findings. The results identify four configurations with an overall consistency of 0.887, and the key driving conditions are largely consistent with those of dynamic QCA. However, static QCA captures only cross-sectional relationships, whereas dynamic QCA further reveals the temporal stability and evolutionary patterns of servitization pathways.

5 Conclusion

Based on the TOE framework, this study applies dynamic QCA to investigate manufacturing servitization paths. The findings reveal that: (1) no single condition is necessary for high servitization, indicating a multifactorial process; (2) two configurations are identified, namely the digital capability-driven path and the innovation talent-supported path, both emphasizing the synergy between R&D intensity and organizational capabilities; (3) temporal, regional, and industrial analyses demonstrate configuration stability while revealing heterogeneous adaptation across contexts.

Based on these findings, several managerial implications are proposed. First, firms should strengthen technological capabilities through digital technology adoption and continuous R&D investment, as these factors play important roles across multiple configurations. Second, firms should enhance organizational capabilities by developing digital talent and improving digital infrastructure to support technology integration and service innovation. Third, policymakers should provide differentiated support by improving regional digital environments and tailoring policies to local conditions.

This study has limitations regarding policy-related factors, such as government subsidies and institutional support, which are excluded due to limited firm-level data availability. Future research could incorporate policy variables into the configurational framework to further examine the interaction between external environments and internal capabilities. Moreover, the sample consists of MIIT-recognized service-oriented manufacturing enterprises, which may introduce selection bias and limit the generalizability of the findings. Future research could extend the sample to broader manufacturing firms to further examine the applicability of the identified configurations.

Disclosure of Interests

The authors have no competing interests to declare that are relevant to the content of this article.

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