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(Research Paper)

Leveraging Emerging Technologies to Create Supply Chain Agility in Iranian Midstream Oil Terminals: A Mixed-Method Grounded Theory-ISM Analysis in the Industry 4.0 Context

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Abstract

Supply chain agility (SCA) is critical for industries operating in volatile environments, yet limited research addresses technology-driven agility in sanctions-constrained contexts. This study investigates how emerging technologies enhance SCA in Iran's midstream oil terminals using a mixed-methods approach combining Grounded Theory (GT) and Interpretive Structural Modelling (ISM). Through interviews with 12 senior managers and a six-expert ISM panel, we identified 17 key factors across causal, contextual, and intervening conditions. The core phenomenon "Technology-Driven Supply Chain Agility" redefines technology from a supporting tool to a strategic imperative. ISM and MICMAC analyses revealed market instability and resource allocation as root drivers, while procurement challenges emerged as highly dependent outcomes. Four strategic frameworks were developed: Information Intelligence (blockchain, AI), Supply Digitalisation (3D printing, ML forecasting), Predictive

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Maintenance (IoT, digital twins), and Enabling Ecosystem Development (VR/AR training). This research advances theory by proposing a GT-ISM integration framework and provides practitioners with a prioritised roadmap for technology investment in high-risk environments.

Keywords: Supply Chain Agility, Midstream Oil Industry, Digital Transformation, Emerging Technologies, Grounded Theory, Oil Terminal

1. Introduction

Supply chain management plays a crucial role in the operational success of industries, significantly influencing productivity, cost-efficiency, and competitiveness. In today's volatile business environment, an organisation's ability to adapt to disruptions and respond swiftly to changing market conditions is critical. The rapid advancement of digital technologies has transformed supply chains and enhanced company agility. Technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), Blockchain, and 3D printing enable organisations to enhance operational efficiency, optimise data management, improve risk prediction, and promote process automation (Queiroz et al., 2022; Zhang et al., 2022). Research indicates that digitising the supply chain can enhance the velocity, adaptability, precision, and efficacy of business operations, while simultaneously decreasing operational costs by over 30%, diminishing the probability of lost sales by more than 60%, and reducing necessary inventory levels by over 70% (Chauhan et al., 2023). Emerging technologies are breakthroughs that can create new entities or transform existing ones, thereby optimising processes in the process industries (Florea, 2024; Yusuf, 2024). Essential characteristics of these technologies include foundational innovation, relatively rapid expansion, coherence, substantial influence, and uncertainty and ambiguity (Rotolo et al., 2015).

The midstream oil sector faces unprecedented challenges: outdated infrastructure, regulatory complexity, and supply chain vulnerabilities (Saran et al., 2024). For Iran's oil terminals, geopolitical factors and economic sanctions intensify these pressures, requiring innovative technological solutions to maintain operational continuity.

While extensive literature examines supply chain agility (SCA) and Industry 4.0 adoption separately, few studies integrate these domains specifically for midstream oil operations under geopolitical constraints. Existing frameworks (Fayezi et al., 2017; Brusset, 2016) treat technology as an enabler but do not address contexts in which traditional agility mechanisms , such as supplier diversification and international partnerships ,are unavailable due to sanctions.

This study primarily investigates the following research question:

1. What are the key factors influencing supply chain agility in Iran's midstream oil terminals within the context of Industry 4.0?
2. How may these factors be prioritised to develop strategic methods for creating agility?
3. What role do new technologies play in creating an agile supply chain?

This research reconceptualises technology's role in SCA from an optional tool to a strategic imperative in constrained environments. It provides actionable guidance for prioritising technology investments in high-risk, resource-limited contexts.

2. Literature Review

2.1 Supply Chain Agility (SCA)

The field of SCA studies has expanded across various dimensions, resulting in a fragmented literature and making the concept somewhat unclear, especially in its definition (Gligor et al., 2013). Some authors define the concept operationally (Brusset, 2016; Yang, 2014), others consider it a management philosophy (Lin et al., 2006), and still others view it from a strategic perspective (Fayezi et al., 2017). Given this field's relative newness, it is unsurprising that there is no agreement on the definition of SCA. SCA is a relatively new area of scholarship, with its first published articles in 1999 (Bal et al., 1999; Mason-Jones & Towill, 1999). Fayezi et al. (2017) define it as "a strategic ability that assists organisations to rapidly sense and respond to internal and external uncertainties," while Atmaja et al. (2022) emphasise its multi-dimensional nature, involving intelligence, mindset, and integrative processes among supply chain members to meet customer needs proactively and predictively. Recent meta-analytic research by Alfalla-Luque et al. (2023), based on 63 empirical studies covering more than 14,000 firms, confirms a significant positive association between SCA and organisational performance across various geographic and industrial contexts, underscoring its value in achieving competitive advantage.

2.2 Midstream oil and gas supply chains

The midstream sector of the oil and gas industry faces unique supply chain challenges, as highlighted by Saran et al. (2024). Key issues include safety concerns, regulatory compliance, escalating costs, and optimisation challenges arising from ageing infrastructure that is often geographically dispersed and vulnerable to security threats, such as theft and cyberattacks. These vulnerabilities can result in production outages and significant health, safety, and environmental damage (Deloitte China,2019). Additionally, Piya et al. (2020) identified critical drivers of SCA in this industry, including senior management commitment, strategic alignment, IT integration, and organisational culture, which are essential for addressing sector-specific challenges.

2.3 Grounded theory in supply chain research

Grounded theory (GT) is a robust inductive methodology in supply chain management (SCM) and is often used to study complex and emergent phenomena. The data-first design of GT allows theories to emerge from the empirical context rather than being grounded in prior theoretical frameworks. For instance, Dalal et al. (2022) employed GT to map supply chain drivers in the handicraft industry, while Pizzichini et al. (2023) used GT to examine how digital servitization aligns with reference frameworks in SCM. GT is also adaptable to study technological innovations, such as blockchain (Rodrigues et al., 2021) and green technologies (Lu et al., 2025).

2.4 Emerging technologies in supply chains

Technologies such as the Internet of Things (IoT), blockchain, artificial intelligence (AI), and Big Data analytics are reshaping traditional supply chains with real-time data visibility, process automation, and predictive capabilities that were previously not feasible (Haddud & Khare, 2020; Khan & Manzoor, 2021; Queiroz et al., 2022). Industry 4.0 technologies are strengthening SCA by enabling organisations to respond more quickly to market changes and deliver data-driven solutions (Dias et al., 2022). Further evidence from Zhang et al. (2022) supports the indication that digital technologies are moving traditional supply chains toward more intelligent, more flexible networks. In the oil and gas sector, AI supports sustainability initiatives (Waqar et al., 2023), while blockchain improves transparency and trust among supply chain actors (Revathi et al., 2024). The deployment of AR (augmented reality) for training and predictive maintenance is yet another area that is bringing tangible improvements (Elkateb et al., 2024; Yoo et al., 2024). Each technology addresses sector-specific challenges and enables more innovative, flexible supply chain models (Olutimehin et al., 2024).

3. Research methodology

3.1 Research design

This study adopts a mixed-method approach, integrating Strauss and Corbin's Grounded Theory (GT) methodology with Interpretive Structural Modelling (ISM) and MICMAC analysis to investigate supply chain agility (SCA) in Iran's midstream oil industry. The research process followed a sequential design, as illustrated in Figure 1.

3.2 Grounded Theory (GT) approach

This study employed purposive sampling to select 12 senior experts and managers from four key organisations in Iran's oil sector. Inclusion criteria required at least 10 years of experience in the oil industry, specialised knowledge in operations or supply chain management, familiarity with the Iranian Oil Terminals Company (IOTC) operations, and a master's degree or higher. Organisation A refers to IOTC, while Organisations B, C, and D represent affiliated upstream companies. For confidentiality, participants were anonymised using codes (PA1–PA12), as detailed in Table 1.

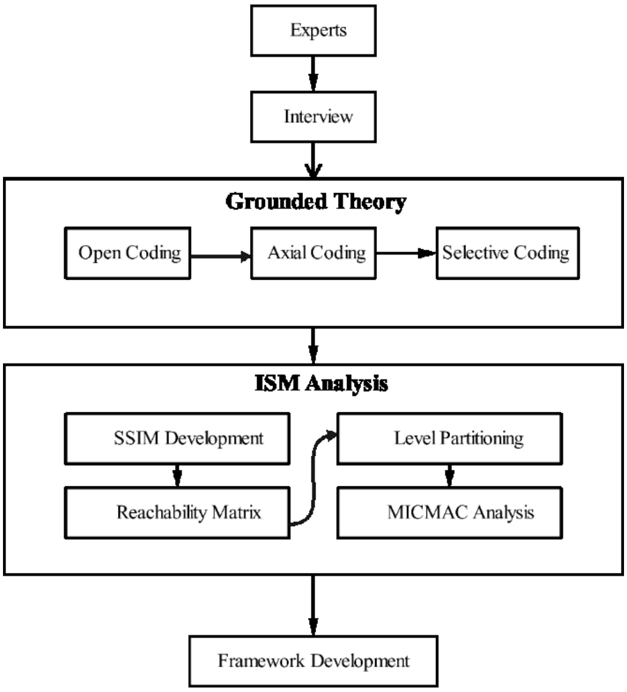

Fig. 1. Research Methodology Framework

Table 1. Demographic information of participants

Participant	Organization	Specialty Area	Position	Years of Experience
PA1	Organization A	Maintenance Engineering	Executive Management	33
PA2	Organization A	Procurement & Logistics	Administration Head	37
PA3	Organization A	Procurement & Logistics	Senior Resource Analysis Expert	17
PA4	Organization A	Technology & Computers	Senior Network Expert	21
PA5	Organization A	Procurement & Logistics	Senior Resource Analysis Expert	19
PA6	Organization A	Technology & Computers	Senior IT Automation Expert	17
PA7	Organization A	Procurement & Logistics	Senior Procurement Expert	15
PA8	Organization A	Technology & Computers	Network Expert	10
PA9	Organization A	Maintenance Engineering	Senior Program Planning Expert	15
PA10	Organization B	Maintenance of Equipment & Facilities	Project Manager	17
PA11	Organization C	Supply Chain Management & Procurement	Senior Procurement & Supply Expert—	15
PA12	Organization D	Procurement	Procurement manager	10

Semi-structured interviews (30–40 minutes each) were conducted with informed consent to identify supply chain challenges, opportunities for improvement, and the role of emerging technologies in enhancing agility. The interview with participants' in-interview reflections and methodological suggestions informing refinements to subsequent interviews. Theoretical saturation was achieved progressively: interviews 1–6 generated 8–12 new codes per session, declining to 3–5 codes in interviews 7–9, with no new codes emerging in interviews 10–12. Sampling followed grounded theory's principle of moving from core to peripheral contexts across two phases. Phase 1 (PA1–PA9) focused exclusively on Organisation A (IOTC), sampling three functional domains: maintenance engineering (PA1, PA9), procurement/logistics (PA2, PA3, PA5, PA7), and IT/automation (PA4, PA6, PA8) to map internal supply chain vulnerabilities. Phase 2 (PA10–PA12) expanded to upstream partners (Organisations B, C, D) to validate emergent themes across NIOC's broader supply network and ensure cross-organisational generalizability.

3.3 Data analysis

3.3.1 Grounded theory analysis

Data analysis using grounded theory followed the three-stage coding process proposed by Strauss and Corbin (1998):

- Open Coding: Initial identification of concepts and themes from qualitative data
- Axial Coding: Organising concepts into categories such as causal, contextual, intervening, strategic, and outcome factors.
- Selective Coding: Integrating categories around a core phenomenon to develop a comprehensive model of SCA.

The analysis was conducted using MAXQDA software to facilitate the organisation and management of qualitative data.

- Sample Interview Excerpts and Coding Process

Table 2 provides examples of raw interview excerpts and demonstrates how open codes were generated and subsequently abstracted into axial and selective codes through the constant comparative method.

The sequence of transforming open codes into axial and then selective codes is presented in the Findings section (Grounded Theory).

Table 2. Coding hierarchy demonstration

Raw Interview Excerpt	Open Code	Axial Category	Selective/Core Category
"Our equipment is all American, European, and Japanese, and these countries have sanctioned us and do not provide parts and equipment." (PA3)	Lack of access to foreign suppliers	Procurement challenges	Technology-driven supply chain agility
"Over the past 10 years, the main problem has been budget. The requests were feasible, but the company's budget was insufficient, which caused work disruptions." (PA4)	Budget allocation delays and operational disruption	Market and price instability	Technology-driven supply chain agility
"The metering systems at Khark terminal are more than 35 years old and require smarter systems." (PA2)	Outdated metering systems require smart upgrades	Infrastructure limitations	Technology-driven supply chain agility
"Preventive maintenance (PM) systems are implemented, but AI algorithms for failure prediction have not yet been used."(PA6)	Lack of predictive maintenance using AI	Equipment monitoring weaknesses	Technology-driven supply chain agility
"In addition to cost, there are factors such as laws and regulations, technological complexity, and human resistance to adopting new technologies."(PA8)	Multiple barriers to technology adoption (cost, regulation, culture)	Cultural and human barriers	Technology-driven supply chain agility

3.3.2 Interpretive Structural Modelling (ISM)

To deepen the understanding of interrelationships among the identified factors, Interpretive Structural Modelling (ISM) was applied. ISM enables hierarchical classification and prioritisation of factors by transforming complex relationships into a structured model. The ISM process involved several steps:

a) Identification of core components from GT findings.

A key methodological choice in this study was to include only causal, contextual, and intervening factors in the ISM analysis, excluding strategies and outcomes. This decision was made for the following reasons:

- Focus on Root Causes: ISM is most effective when applied to problem-oriented variables that represent underlying drivers rather than solutions. By excluding strategies, the analysis concentrates on identifying fundamental forces and barriers that must be addressed.
- Practical Prioritisation: By modelling only root-cause factors, decision-makers can identify which fundamental issues to address first, and subsequently apply appropriate strategies based on the hierarchical structure revealed.

b) Development of a structural self-interaction matrix and reachability matrix.(See the Apindex)

The ISM process engaged six senior experts from the GT participant pool, selected based on at least 15 years of IOTC experience and involvement in strategic decision-making. Consensus was achieved through a structured voting mechanism: experts received initial briefings on the nine factors and ISM methodology, then independently assessed pairwise relationships using the SSIM framework. Each relationship was determined by majority rule if at least four out of six experts (67% threshold) agreed on a specific relationship type (e.g., V, A, X, or O); that relationship was incorporated into the final SSIM. For cases with three-to-three vote splits, experts engaged in evidence-based discussion until a clear majority emerged. This transparent, vote-based approach ensured methodological rigour while grounding the ISM model in collective expert judgment rather than individual opinion.

c) Application of the transitivity rule and hierarchical structuring of factors. (Fig. 2)

d) Use of MICMAC analysis to categorise variables based on driving power and dependence. (Table 8 - Figure 3)

3.4 Rigor

University professors and industry experts evaluated the data-collection tools (interview questions) used in this study to assess content validity. The feedback from these specialists was used to refine and finalise the question framework. To assess the reliability of the qualitative analysis, the researcher coded the data at two distinct time points and subsequently calculated the level of agreement between the two rounds. An agreement rate of 80% signified a high degree of reliability in the qualitative analysis.

3.5 Ethics statement

This research adhered to ethical guidelines for studies involving human participants. Participants were informed about the study’s purpose, the voluntary nature of participation, their right to withdraw, and data usage protocols. Confidentiality was maintained by coding participating organisations as B-D and assigning anonymous identifiers (PA1-PA12) to individuals, as shown in Table 2. The study focused on organisational systems rather than individual case reports, using a GT approach to analyse expert insights in the midstream oil industry.

4. Findings

4-1 Grounded theory analysis results

The grounded theory analysis of interview data identified 17 key components of supply chain agility in the oil terminal industry. The paradigm model categorises these components as follows:

4-1-1 Causal Conditions

Causal conditions are the factors that trigger or explain the occurrence of the core phenomenon, such as the motivations or pressures for adopting agile supply chains (Zahedifar et al., 2021). The causal conditions were categorised into four main types (Table 3).

Table 3. Causal conditions

Component	Main categories	Subcategories
Causal Conditions	Procurement challenges	Delays in supplying critical and essential parts
		Lack of access to foreign suppliers
		High dependency on imports.
		Bureaucracy in administrative processes
	Market and price instability	Delays in securing the necessary budget for orders
		Fluctuations in equipment and parts prices
		Planning problems
		Reduction in suppliers' financial commitments
	Equipment Monitoring	Equipment wear and corrosion
		Need for periodic repairs.
		Shortage of spare parts
		Lack of online monitoring in pipelines and tanks
		Conventional leak detection methods
		Physical leak detection and a lack of advanced digital systems
		Limited use of marine robots (ROVs[2])
		Difficulty in monitoring due to the vast and scattered locations
		Operational limits and safety risks in remote or underwater areas
	Weak Coordination	Delay in sending requests
		Scattered information
		Absence of centralised equipment monitoring
		Absence of shared data management systems between different departments
		Impact of slow information flow on real-time decision-making

[2] Remotely Operated Vehicles

4.1.2 Contextual conditions

Contextual conditions refer to the factors or circumstances that describe the environment in which the phenomenon occurs, including characteristics that may influence it (Tashtzar et al., 2023). The contextual conditions were categorised into three main types (Table 4).

Table 4. Contextual conditions

Component	Main categories	Subcategories
Contextual Conditions	Infrastructure Limitations	Outdated measurement systems (metering)
		Challenges in safeguarding industrial data on local servers
		Limited access and remote collaboration capabilities
		Lack of predictive systems for equipment failures and smart repairs
		Software update problems due to outdated hardware
	Supply Chain Complexity	Oil terminals at NIOC's [3] supply chain end
		High dependency on upstream companies
		Lack of a centralised information bank in the Ministry of Oil
	Legal and Managerial Constraints	Lengthy approval processes
		Strict auditing requirements
		Senior management decisions

4.1.3 Intervening conditions

Intervening conditions are therefore the factors that emerge during the process under study and modify how people respond to the situation through their actions and interactions (Strauss & Corbin, 1998). The intervening conditions were categorised into two main types (Table 5).

Table 5. Intervening Conditions

Component	Main categories	subcategories
Intervening Conditions	Resource Allocation	Focus on ongoing operations rather than new technologies
		Economic pressures
		Uncertainty about outcomes
	Cultural and Human Barriers	Lack of technical skills
		Lack of motivation
		Resistance to digitalisation
		Differing mindsets
		Need for specialised training.

[3] National Iranian Oil Company

4.1.4 Action/interactional strategies

Strategies (action/interaction) are deliberate responses people make to handle situations, problems, or issues under specific conditions. These responses are not random but are purposeful actions embedded in a network of past, present, and anticipated future interactions (Strauss & Corbin, 1998).

The action/interactional Strategies were categorised into four main types (Table 6).

Table 6. Action/interactional strategies

Component	Main categories	Cubcategories
Strategies	Information Intelligence	Reduction of bureaucratic approval processes
		Automatic interdepartmental coordination
		Information integration
		Facilitation of decision-making
		Prediction of future needs
	Supply digitalization	Preventive procurement of parts
		Localisation of critical parts
		dependency on foreign suppliers
		Circumventing sanctions
		Digitalisation of ordering and inventory management
	Preventive Maintenance	Advanced process monitoring
		Use of underwater robots
		Smart metering systems
		Predictive alerts/warnings
		Optimising maintenance cycles
	enabling ecosystem development	Collaboration with knowledge-based companies
		Investment in domestic R&D projects
		Leveraging government support mechanisms
		Facilitating change and training processes

The first strategy, information intelligence, aims to optimise the flow and management of information across the supply chain by leveraging emerging technologies. By doing so, it directly addresses challenges in information and decision-making processes, thereby enhancing the efficiency of the entire supply chain and improving decision accuracy.

The second strategy, termed supply digitalisation, employs advanced technologies to enhance supply processes. These technologies significantly enhance the efficiency and precision of supply operations by facilitating the localisation of essential parts and components. Moreover, they reduce reliance on external suppliers, mitigate the risk of financial penalties and currency fluctuations, and ultimately enhance the supply chain's flexibility and robustness.

The third strategy, predictive maintenance, uses advanced technologies to simulate equipment performance. This strategy directly addresses challenges related to equipment monitoring and infrastructure limitations.

The fourth strategy, Enabling Ecosystem Development, although not directly focused on emerging technologies, serves as a strategic foundation for technology development and accelerates the innovation process within oil terminal companies. It plays a crucial role in creating the necessary infrastructure for the adoption of advanced technologies. Furthermore, the strategy promotes technological progress and innovation by collaborating with knowledge-based companies to localise technical expertise and invest in research and development.

4.1.5 Outcomes

Outcomes are the results or consequences of implemented strategies. These results can indicate the success or failure of the adopted strategies (Lee & Song, 2021). The outcomes were categorised into four main types (Table 7).

Table 7. Outcomes

Component	Main categories	Subcategories (initial codes)
Outcomes	Accurate and real-time Information Flow	Implementation of intelligent monitoring systems
		More up-to-date and accurate information
		Improved information transparency
		Increased speed of managerial decision-making
	Reduced Dependence on Foreign Suppliers	Localisation of parts
		Improved cooperation with domestic suppliers
		Reduced risks from sanctions, bans, and severed international trade relations.
		Enhanced self-sufficiency in supplying strategic parts
	Reduced Operational Downtime	Improved maintenance processes
		Use of predictive systems
		Rapid problem identification through real-time data
		Rapid parts supply processes
	Reduced Operational Risk	Preventive and proactive management of incidents
		Increasing risk readiness in critical situations
		Flexible and rapid response in crisis conditions
		Minimisation of human errors

4.1.6 Core category

The core category serves as a central concept around which all other categories and codes are structured. The primary criterion for recognition of the core category is its repeated appearance in the data (Khajavi & Rezaei, 2019). In our study, the core concept of "technology-driven supply chain agility" is logically and cohesively linked to all other aspects of the model. Causal challenges, such as market instability and procurement issues, underscore the need for technology-driven solutions. Contextual factors, such as supply chain complexity and infrastructure limitations, define an environment in which technology is the most effective tool for achieving agility. Intervening factors, such as resource constraints and human resistance to change, also influence the implementation of this technology-driven approach. All proposed strategies focus on the targeted application of emerging technologies, and the positive outcomes resulting from their implementation confirm the effectiveness of this approach. Therefore, this concept reflects a paradigm shift in the industry, in which technology no longer merely plays a supporting role but is a fundamental factor in achieving supply chain agility in a volatile, complex environment.

4.2 ISM analysis results

4.2.1 ISM hierarchical model

Based on the level partitioning results, an ISM hierarchical model was developed, as shown in Figure 2. This model illustrates the relationships between the factors affecting supply chain agility in IOTC, with those at higher levels being more dependent and those at lower levels having higher driving power.

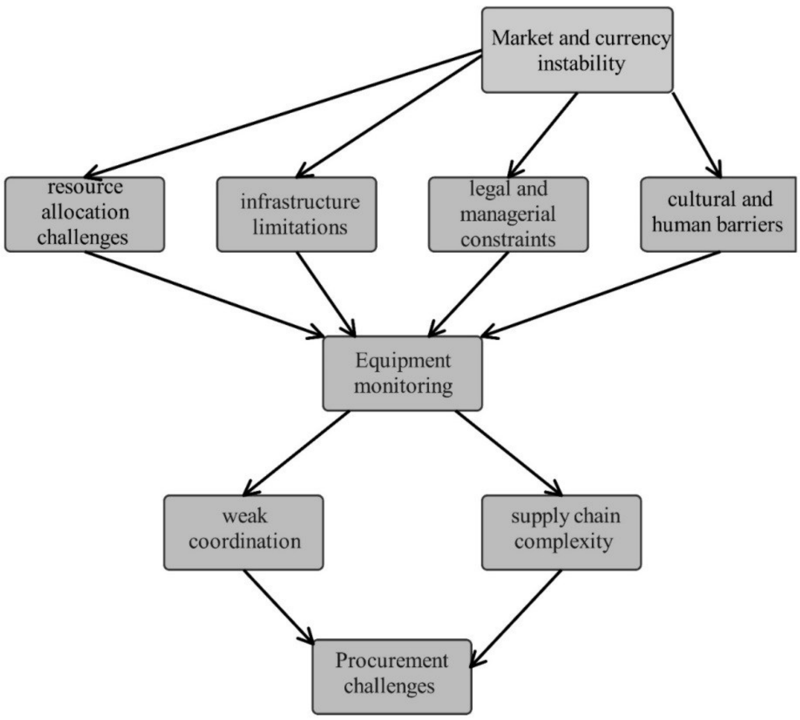

Fig. 2. ISM hierarchical model

4.2.2 MICMAC analysis

The MICMAC analysis categorised the factors into four clusters based on their driving power and dependence: autonomous (drivers), dependent, linkage, and independent (drivers). The results are presented in Table 8 and Figure 3.

Table 8. MICMAC Analysis Results

Factor	Driving Power	Dependence	Variable Type	Level	Impact
Procurement challenges	1	9	Dependent	I	Low driving, High dependence
Market and currency instability	9	1	Independent	V	High driving, low dependence
Equipment monitoring	7	6	Linkage	III	Medium driving, medium dependence
Weak coordination	3	8	Dependent	II	Low driving, high dependence
infrastructure limitations	8	6	Linkage	IV	Medium driving, medium dependence
Oil supply chain complexity	3	8	Dependent	II	Low driving, high dependence
Legal and Managerial Constraints	8	6	Linkage	IV	High driving, medium dependence
Resource allocation	8	5	Independent	IV	High driving, medium dependence
Cultural and human barriers	8	6	Linkage	IV	Medium driving, medium dependence

The MICMAC analysis reveals that

- Market and currency instability (1) and resource allocation challenges (2) are independent variables with high driving power and low dependence.
- Equipment monitoring (6), infrastructure limitations, legal and managerial constraints, and cultural and human barriers (3, 4, 5) are linkage variables with medium to high driving power and medium dependence.
- Procurement challenges (9), weak coordination, and supply chain complexity (7, 8) are dependent variables with low driving power and high dependence.

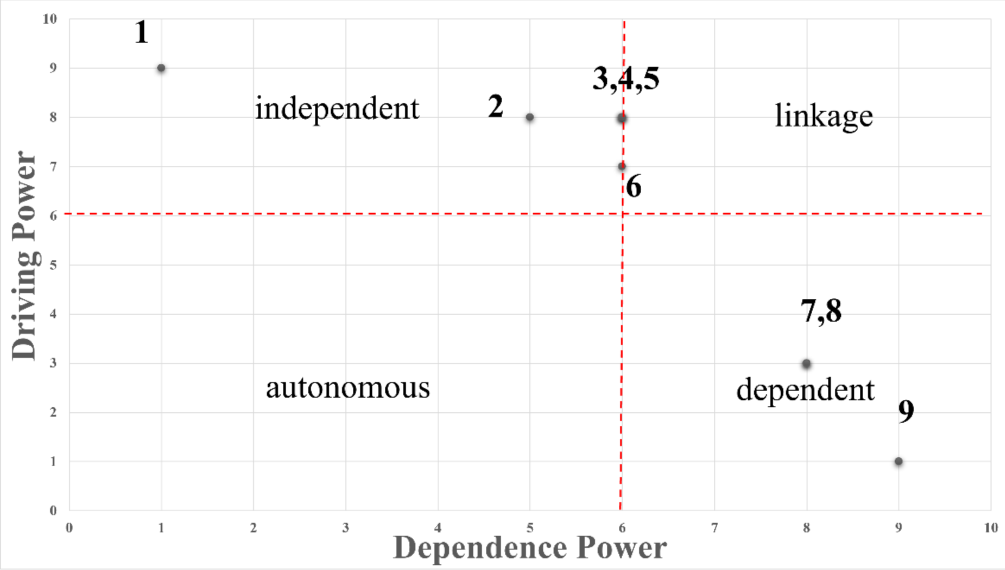

Fig. 3. MICMAC analysis matrix

5. Discussion

The ISM hierarchical model (Fig. 2) shows that market instability and resource allocation constraints (Level V independent variables) drive mid-level factors such as infrastructure limitations, legal constraints, and cultural barriers (Levels III-IV). These mid-level factors then create operational problems like procurement challenges and coordination weaknesses (Levels I-II). This hierarchy challenges conventional approaches that focus on fixing operational issues; our findings show these operational problems are *symptoms* that require addressing root causes first.

The integration of GT and ISM reveals a clear pathway from challenges to solutions .The four GT-derived strategies directly correspond to specific ISM levels:

• Information Intelligence (blockchain, AI, cloud) targets challenges across Levels II-V by creating data-driven decision-making infrastructure. This addresses both coordination weaknesses and market volatility.

- Supply Digitalisation (3D printing, ML [4]forecasting) resolves Level I procurement dependencies by enabling local production and reducing reliance on foreign suppliers, which is essential in sanctioned environments.
- Predictive Maintenance (IoT, digital twins, robotics) addresses Level III-IV infrastructure and monitoring challenges, preventing operational disruptions before they affect dependent variables.

[4] Machine Learning

- Enabling Ecosystem Development VR[5]/AR[6] training, innovation partnerships) tackles Level IV cultural barriers that block technology adoption, building organisational readiness.

Both GT and ISM converge on "Technology-Driven Supply Chain Agility" as the central concept. GT established this through systematic coding; ISM validated it structurally by demonstrating that technology-enabled strategies provide the only effective pathways from independent (driving) variables to dependent (symptom) variables in this constrained environment.

Table 8 outlines the key strategies that the IOTC should implement to address supply chain issues, along with the emerging technologies that facilitate their execution to create an agile supply chain. These strategies, derived from the Grounded Theory section, can be operationalised and implemented using these technologies to create a more agile supply chain.

Table 8. Technology-enabled agility strategies

Strategy	Core Technologies	Target Challenges (ISM Level)	Influence Type
Information Intelligence	• Blockchain • AI-based systems • Cloud ERP[7]	• Market instability (V) • Resource allocation (IV) • Weak coordination (II)	Independent + Dependent
Supply Digitalization	• 3D printing • ML forecasting • Automated inventory	• Procurement delays (I) • Supplier dependency	Highly Dependent
Predictive Maintenance	• IoT sensors • AI analytics • Digital twins • Robotics	• Infrastructure aging (IV) • Equipment monitoring (III)	Linkage
Ecosystem Development	• VR/AR training • Knowledge platforms • AI chatbots	• Cultural resistance (IV) • Skill gaps	Linkage

Note: ISM levels indicate hierarchical position (I=highest dependency, V=highest driving power). Influence types correspond to MICMAC classifications.

Incorporating blockchain and smart contracts enhances transparency, traceability, and security, thereby reducing currency-related disputes and improving trust among stakeholders (Hewa et al., 2021; Macrinici et al., 2018). Smart contracts automate and enforce agreements

[5] Virtual Reality
[6] Augmented Reality
[7] Enterprise resource planning

without central authorities, offering transparent, self-executing processes that help mitigate risks and disputes in volatile currency environments (Ante, 2020; Wang et al., 2019). Additionally, blockchain-based smart contracts have been shown to stabilise exchange rates and commit parties to dynamic policies that address speculative attacks and volatility (Routledge & Zetlin-Jones, 2021; Zhang et al., 2024). Some frameworks allow sensitive financial data to be shared privately between contracting parties, while non-sensitive information is made public, balancing transparency with confidentiality (Zhang et al., 2024).

AI resource-optimisation frameworks use predictive analytics tools to identify which projects to prioritise, manage budgets, and allocate resources efficiently based on ROI analysis, thereby supporting strategic planning and informed decision-making. AI techniques such as linear programming, genetic algorithms, and neural networks optimise resource allocation, including personnel and equipment, thereby improving resource utilisation, reducing costs, and shortening project timelines (Sravanthi et al., 2023).

To overcome legal and managerial barriers that limit supply chain agility, an integrated compliance management system based on artificial intelligence and blockchain is introduced (Jain et al., 2024; Tiwari et al., 2024). This system includes an intelligent module that automatically analyses regulatory texts and provides managers with structured summaries of key legal requirements. AI-driven tools continuously monitor operational data such as contracts, transactions, and customs activities against legal obligations and issue early warnings to identify potential risks.

According to Schniederjans and Hales (2016), cloud-based SCM solutions significantly improve cross-functional collaboration and information sharing. Private cloud systems are designed to provide enhanced security measures, such as encryption and access control, to protect sensitive data and ensure that only authorised users can access it (Brandao, 2020). Additionally, these systems are built to be scalable, allowing organisations to efficiently manage fluctuating workloads and integrate seamlessly with existing IT infrastructure, thereby supporting both legacy and modern systems (Irshad et al., 2023; Balakrishanan et al., 2024).

Private blockchains play a crucial role in enabling secure local transaction management and decentralised document storage, effectively reducing corruption and ensuring the fast, reliable recording of sensitive data (Vashistth et al., 2019). In complex oil supply chains with multiple stakeholders, blockchain creates an immutable record of all transactions and product movements. This eliminates information asymmetry, which has traditionally complicated midstream operations.

By adopting 3D printing, companies can keep a smaller inventory of digital models ready for production, which can be printed as needed (Oudheusden et al., 2024). Moreover, adopting a localised production model can enhance supply chain resilience and efficiency, particularly in offshore and remote operations, where the availability of spare parts is critical (Westerweel et al., 2021). By using artificial intelligence (AI) tools, particularly predictive analytics, companies can forecast demand for spare parts based on historical data and external parameters, including global oil trends and currency fluctuations (Kim et al., 2023). An AI-based market forecasting system with an intuitive dashboard can help supply chain managers reduce risk, optimise purchasing, and negotiate better by providing accurate demand forecasts, improving inventory management, and enabling proactive responses to market changes (Borah et al., 2024; Ellaturu & Rajalakshmi, 2024; Wasik et al., 2024).

IoT enhances operational efficiency by installing smart sensors on critical equipment, such as pumps and compressors, to collect real-time performance data. This data is used for predictive maintenance through localised systems, such as edge computing, to ensure timely interventions and reduce downtime (Zaidi et al., 2024). To upgrade legacy systems to an innovative, IoT-like network, key operational components, such as PLCs and DCSs, are first assessed and mapped. Instead of costly replacements, compatible gateways and adapters are used to connect existing equipment to modern platforms (Alqoud et al., 2022; Rosas et al., 2017; Tiwari & Shanmugam, 2024). These gateways handle protocol translation (e.g., Modbus-to-MQTT) and implement cybersecurity measures, such as network segmentation and encrypted channels, to mitigate risks associated with connecting previously isolated systems (Alqoud et al., 2022; Rosas et al., 2017). A secure private cloud then collects, standardises, and stores essential data, enabling real-time monitoring and smarter, centralised decision-making at minimal cost (Alqoud et al., 2022).

Digital twins create virtual replicas of physical equipment, enabling accurate simulations and predictive analyses that facilitate proactive maintenance and optimise resources, such as storage capacity (van Dinter et al., 2022). Machine learning algorithms trained on historical operational data enable predictive maintenance systems to detect and predict equipment failures effectively. This approach enables informed decision-making and reduces operational risk. A systematic literature review highlighted the importance of machine learning methods in predictive maintenance applications, emphasising their role in preventing equipment failures and optimising maintenance strategies (Carvalho et al., 2019). Another study on industrial applications demonstrated the use of machine learning algorithms, such as AdaBoost, to classify machine stops in real time, thereby improving efficiency and productivity (Elkateb et al., 2024). Additionally, drones and inspection robots are deployed for aerial inspections of pipelines and for performing high-risk maintenance tasks in hazardous or hard-to-reach locations, thereby significantly improving safety and operational efficiency (Wang et al., 2019).

In the realm of training, augmented reality (AR) platforms offer innovative solutions for employee training. These platforms enable hands-on learning in simulated environments, which facilitates practical skill development without disrupting operational workflows. AR systems, when combined with AI capabilities, can adaptively tailor instructions and feedback to meet users' specific needs, enhancing the training experience (Yoo et al., 2024).

A detailed analysis of the data using Strauss and Corbin's grounded theory method has yielded a combined theoretical model that shows how new technologies and supply chain agility interact in the midstream oil industry. Figure 2 illustrates this model, in which technology is not merely a supportive component but the primary driver of supply chain agility in a rapidly changing work environment.

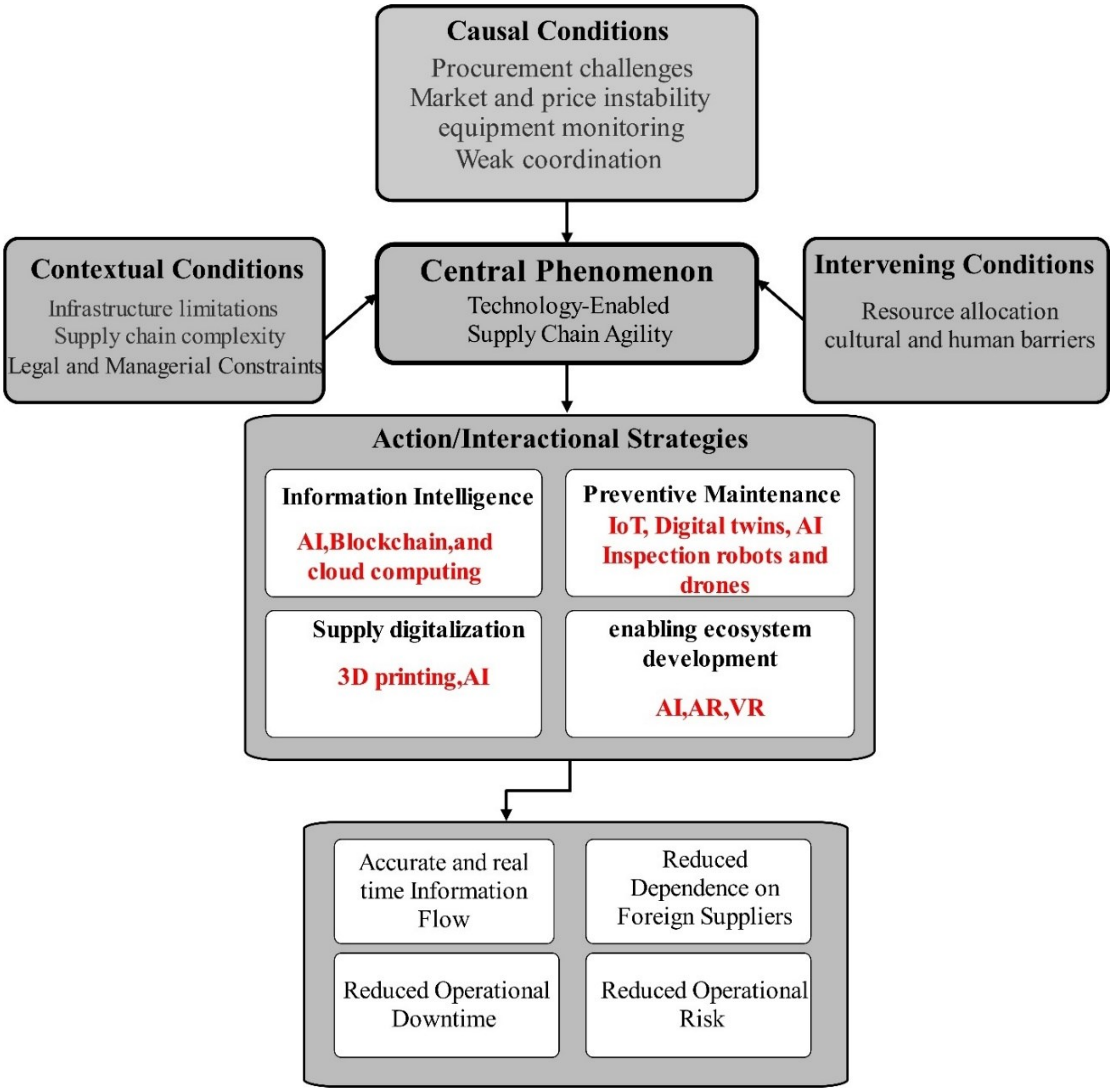

Fig. 4. An agile supply chain framework focused on emerging technologies strategies for midstream oil companies

6. Conclusions

This study reconceptualises supply chain agility in midstream oil operations by positioning technology as a strategic imperative rather than a discretionary facilitator. Employing integrated GT-ISM methodology, we identified hierarchical interdependencies among agility determinants and developed four technology-centric strategies calibrated for sanctions-constrained environments. Findings show that Market volatility and resource allocation constitute fundamental independent variables (ISM Level V), whereas operational inefficiencies manifest as dependent symptoms requiring upstream intervention. Technology-mediated strategies emerge as primary viable mechanisms when conventional agility drivers are systematically constrained. Phased implementation, prioritising high-driving-power factors, optimises resource allocation efficiency in resource-limited contexts.

This study makes three key contributions to the literature on supply chain agility and Industry 4.0 in midstream oil operations. First, it reframes technology from a secondary enabler (Brusset, 2016; Fayezi et al., 2017) to a strategic necessity. Grounded theory findings show that under sanctions, conventional agility drivers are ineffective without technological mediation, positioning "Technology-Driven Supply Chain Agility" as the core construct. Second, it presents the first GT–ISM integration in SCA research for the oil and gas sector, combining inductive theorisation with structural hierarchy to deliver a coherent theory-to-practice model. Third, it offers a context-specific technology strategy map. Unlike generic Industry 4.0 frameworks (Queiroz et al., 2022) or single-technology studies (Waqar et al., 2023), the framework integrates multiple technologies across four strategic pathways to address midstream operational constraints. It provides a practical roadmap for managerial prioritisation and sequencing of digital initiatives. For organisations such as IOTC, this research provides an evidence-based technology investment roadmap that prioritises interventions by causal influence rather than symptom visibility.

6.1 Research limitations and future study agenda

The research limitations are as follows:

- Confidentiality restrictions prevented validation through performance metrics (e.g., downtime, procurement cycles, ROI); combining qualitative GT with quantitative analyses would strengthen causal claims.
- Due to the busy schedules of senior executives in the industry, access to some key experts was restricted.
- Purposive sampling within state-owned oil organisations constrained perspective diversity; future research should include private-sector and international experts.

- Findings reflect Iran's midstream operations and may not generalise to unconstrained settings or other industries.
- Limited executive availability and the resource-intensive nature of GT may have excluded additional stakeholder perspectives, despite achieving saturation at 12 interviews.

Future research can focus on comparative studies with international best practices, economic analyses of technology adoption in Iran’s context, and environmental impact assessments aligned with Iran’s carbon-reduction commitments.

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Appindex:

Based on expert consensus, pairwise relationships between the nine factors were documented in the SSIM. Appendix 1 presents the complete SSIM.

Appendix 1. Structural Self-Interaction Matrix (SSIM)

Factor	(1) Procurement	(2) Market Instability	(3) Equipment Monitoring	(4) Weak Coordination	(5) Infrastructure	(6) SC Complexity	(7) Legal Constraints	(8) Resource Allocation	(9) Cultural Barriers
Procurement challenges	-	A	A	O	A	X	A	A	O
Market and currency instability		-	O	O	V	V	A	V	O
(3) Equipment monitoring			-	V	A	V	O	A	A
(4) Weak coordination				-	A	V	A	A	A
(5) Infrastructure limitations					-	V	A	A	A
(6) Oil supply chain complexity						-	A	A	O
(7) Legal and managerial constraints							-	V	V
(8) Resource allocation								-	V
(9) Cultural and human barriers									-

SSIM Notation System:

- V: Factor i influences factor j, but j does not influence i
- A: Factor j influences factor i, but i does not influence j
- X: Factors i and j influence each other (bidirectional)
- O: Factors i and j do not influence each other

The SSIM was converted into a binary reachability matrix using the following transformation rules:

- If SSIM(i,j) = V, then Reachability(i,j) = 1 and Reachability(j,i) = 0
- If SSIM(i,j) = A, then Reachability(i,j) = 0 and Reachability(j,i) = 1
- If SSIM(i,j) = X, then Reachability(i,j) = 1 and Reachability(j,i) = 1
- If SSIM(i,j) = O, then Reachability(i,j) = 0 and Reachability(j,i) = 0

The transitivity rule was applied to account for indirect relationships: if factor i influences factor j, and factor j influences factor k, then factor i also influences factor k. Entries added through transitivity are marked with an asterisk.

Appendix 2. Final reachability matrix (with transitivity)

Factor	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	Driving Power
Procurement challenges	1	0	0	0	0	0	0	0	0	1
Market and currency instability	1	1	1*	1*	1*	1	1	1	1*	9
Equipment monitoring	1	0	1	1	1	1	1*	0	1*	7
Weak coordination	1	0	0	1	0	1	0	0	0	3
Infrastructure limitations	1	0	1	1	1	1	1	1*	1	8
Oil supply chain complexity	1	0	0	1	0	1	0	0	0	3
Legal and managerial constraints	1	0	1*	1	1	1	1	1	1	8
Resource allocation	1	0	1	1	1	1	1*	1	1*	8
Cultural and human barriers	1*	0	1*	1	1	1*	1*	1	1	8
Dependence	9	1	6	8	6	8	6	5	6	-

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