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Investigating and Ranking the Factors Affecting Integrated Supply Chain Performance in Context of Industry 4.0 by Using Fuzzy ANP Method

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Abstract

This study presents a systematic review aimed at exploring the impact of Industry 4.0 technologies on supply chain transparency and operational enhancement. The research seeks to pinpoint and prioritize the key elements influencing the effectiveness of integrated supply chains within the Industry 4.0 framework. To address existing theoretical gaps, a research model was developed. The study population included executives from automotive firms listed on the Tehran Stock Exchange, who responded to a structured questionnaire. Based on data analysis, 70 key factors were recognized. These factors were then ranked using the fuzzy ANP method. The results reveal that socio-cultural compatibility with supply chain integration is the most critical factor. It is followed by Technical aspects, legal/Environmental/Financial considerations, and Technological components, respectively, in terms of their significance to integrated supply chain performance.

Keywords: Integrated Supply Chain; Industry 4.0; Fuzzy ANP.

1. Introduction

The supply chain represents a vital system that bridges an organization's resources and its final products (Jaafarnejad, 2018). It encompasses an integrated set of processes (from product design and sourcing to production, distribution, and returns) spanning from suppliers to end-users. Furthermore, it involves aligning internal operations with the perspectives of external customers (Jaafarnejad, 2016). With the advent of the fourth industrial revolution, widely known as Industry 4.0, which merges digital and physical systems through advanced information and communication technologies, companies now have expanded capabilities to optimize resources, reduce waste, and improve operational efficiency (Bayokuzkan & Kocer, 2017).

As industries shift toward digitalization at an accelerated pace, Iranian automotive firms face increasing difficulty in implementing a unified supply chain using traditional or solely sustainable methods. Industry 4.0, by enhancing automation and minimizing manual intervention, has emerged as a path toward achieving environmentally responsible outcomes (Jaafarnejad et al., 2018). Nevertheless, supply chain systems, tasked with managing internal workflows and external partnerships, are becoming increasingly intricate (Fore et al., 2020). Leveraging Industry 4.0 technologies within automotive supply chains can lead to substantial cost reductions and performance gains. These digital tools provide comprehensive visibility (from raw material acquisition to product delivery) offering a strategic advantage (Ng T.C., 2022). Among the notable benefits are minimized human mistakes, real-time inventory monitoring, and precise identification of utilized components via digital platforms. Incorporating these practices is crucial for

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manufacturing enterprises aiming for global competitiveness. Accordingly, embracing Industry 4.0 solutions not only fosters innovation but also promotes sustainable, future-ready supply chains (Yadav et al., 2020).

This study seeks to categorize and examine the key elements (including both primary criteria and their subcategories) that influence the effectiveness of the automotive supply chain when applying Industry 4.0 technologies. To this end, a systematic literature review was conducted, selecting the most pertinent research aligned with the topic. The extracted factors were classified into four overarching domains: technical, environmental-legal, technological, and socio-cultural. Given the challenges confronting the automotive supply chain, this study attempts to identify and prioritize those factors that have the greatest impact on the performance of integrated supply chain systems within the Industry 4.0 paradigm in the Iranian automotive sector. The core objectives of this research are defined as follows:

- To determine the influential factors shaping the efficiency of integrated supply chains under Industry 4.0 frameworks in the automotive field;

- To prioritize these factors based on their relevance and impact.

To achieve these objectives, the study addresses three central research questions:

1. Which aspects should be considered by decision-makers during the design and advancement of integrated supply chains?

2. What are the primary influences on the performance of such supply chains operating within Industry 4.0 settings?

3. How can these influences be effectively ranked in terms of importance and contribution?

The results of this research aim to support practitioners in capitalizing on modern business opportunities by strategically managing supply chain performance drivers. The structure of the paper proceeds as follows: Section 2 presents a literature review on supply chains and Industry 4.0; Section 3 outlines the methodology, including the application of Fuzzy DEMATEL and Fuzzy ANP; Section 4 delves into data analysis; and the final section discusses limitations and proposes avenues for future research.

2. Literature review

Over the past few decades, one of the pivotal aspects contributing to industrial development has been the establishment of efficient systems for supply, production, and distribution collectively known as the supply chain. The emergence of Industry 4.0 has catalyzed a new era of operational digitalization, driving a fundamental transformation in how processes are managed and optimized. The fourth industrial revolution emphasizes the creation of interconnected global networks within smart factories, where machines can autonomously interact, exchange data, and coordinate processes to carry out routine operations. This digital evolution redefines supply chain management through the lens of Industry 4.0 by incorporating cutting-edge innovations such as the Internet of Things (IoT), robotics, wireless communication, and data-driven analytics. These technologies aim to enhance functionality, add value, and elevate customer satisfaction (Kumar et al., 2021).

Industry 4.0, often referred to as I4.0, marks a turning point in the industrial world by fusing digital technologies with physical infrastructure. Its transformative strength lies in enabling real-time collaboration, intelligent automation, and unparalleled efficiency across various sectors. Core components such as artificial intelligence (AI), big data analytics, IoT, and cyber-physical systems are redefining operational dynamics and competitive strategies for organizations. Through real-time data integration, predictive analytics, and automation, Industry 4.0 significantly boosts manufacturing productivity and strengthens supply chain performance (Tahsina Khan & Md Mehedi Hasan Emon, 2025).

2.1. Supply chain

2.1.1. What is a Supply Chain?

As defined by Stefanou (1999), the supply chain consists of interconnected entities including suppliers, manufacturers, wholesalers, retailers, and final consumers, all functioning to balance demand and supply. In an orchestrated supply chain, all involved parties (from producers and vendors to customers) act in unison to deliver a unified offering that aligns with customer expectations. This collaborative ecosystem utilizes shared resources efficiently to provide high-quality products or services at a competitive price point, ensuring greater market accessibility (Turban et al., 2015).

2.1.2. Supply Chain Models

The structure of a supply chain largely depends on the organization's business model. For instance, under a make-to-order (MTO) model, there's minimal need for storing finished goods, though raw materials and parts must be readily available. Supply chains may take various forms such as build-to-stock systems, continuous flow models, configure-to-order strategies, channel-based assembly networks, or globally distributed supply frameworks (Jaafarnejad et al., 2018).

2.1.3. Integrated supply chain

Integration in the supply chain refers to a strategic alignment where legally distinct organizations collaborate so seamlessly that they operate as a unified body. This collaborative mechanism ensures that producers, suppliers, and distributors synchronize their efforts to fulfill customer needs precisely, efficiently, and cost-effectively (Alasdair, 1960). Jafarnejad (2018) outlines eight key managerial dimensions of integration:

1. Customer communication management
2. Customer service coordination
3. Demand planning
4. Order processing
5. Production flow oversight
6. Supplier relationship management
7. Product development and commercialization
8. Returns and reverse logistics management

Given the semi-autonomous nature of each supply chain partner, any change in one participant's condition could directly influence the performance of others, as well as the overall chain. Hence, a fully integrated management system is often considered the most effective method for managing market fluctuations and optimizing inventory levels (Jaafarnejad, 2016). Moreover, the adoption of Industry 4.0 (I4.0) technologies has shown a significant positive correlation with improved supply chain performance. Innovations like real-time data analytics, automation, and cyber-physical systems empower companies to meet shifting market demands, reduce costs, and boost customer satisfaction. For policymakers, these findings serve as a foundation for developing supportive strategies that enable digital transformation and bolster international competitiveness (Tahsina Khan & Md Mehedi Hasan Emon, 2025).

2.1.4. Enabling technologies in the supply chain

The evolution of industrial revolutions began in the late 18th century, where the use of steam power initiated a major shift in societal and industrial functions (Xu et al., 2018). This was followed by the second revolution, driven by the introduction of electricity, petroleum-based energy, and communication systems, which significantly altered production structures (Mokyr & Strotz, 1998). The third phase emerged during the 20th century with the integration of information technology (IT), reshaping work environments and cognitive frameworks (Fitzsimmons, 1994).

Currently, the Fourth Industrial Revolution (described as a systemic transformation across industries and society) brings advanced, interconnected technologies that redefine operational paradigms (Philbeck & Davis, 2018). It encompasses tools such as machine-to-machine (M2M) interactions, Internet of Things (IoT), cyber-physical systems (CPS), artificial intelligence, and big data analytics, enabling rapid data processing at lower operational costs. Despite the promises of Industry 4.0, misaligned adoption of its technologies can lead to significant financial losses and operational inefficiencies, particularly in supply chain contexts. To overcome these challenges, businesses must identify and leverage the appropriate enablers to enhance sustainability and optimize supply chain operations (Surjit Beck et al., 2018).

Supply Chain Automation (SCA) plays a key role in this landscape. It refers to the digital orchestration of financial transactions, logistical flows, operational activities, and information exchange among supply chain partners. Integrating disruptive innovations reduces the need for human intervention and extends automation beyond the production floor to include smart warehousing, logistics, and supply chain management (SCM). Some notable advancements include Autonomous Storage and Retrieval Systems (ASRS), guided vehicles, drones, and AI-integrated warehouse systems offering real-time oversight, safety, and analytics. Additionally, technologies such as additive manufacturing, augmented reality, digital twins, cognitive robotics, embedded IoT, edge computing, and sensor-based infrastructures contribute to creating a connected, intelligent manufacturing environment. Industry 4.0

also transforms customer engagement through tools like AI-powered chatbots, smart products, Internet of People (IoP), and social platform analytics. The resulting autonomy allows for proactive anomaly detection, adaptive production-delivery systems, accurate capacity forecasting, and predictive maintenance (all through cohesive machine-human coordination) (Ghobakhloo et al., 2025).

2.2. Industry 4.0

The term (Industry 4.0) was officially introduced during the 2011 Hannover Trade Fair in Germany. This concept encapsulates the integration of digital advancements that elevate manufacturing and industrial processes to a more adaptive and intelligent level.
The foundational technologies behind Industry 4.0 (namely Cyber-Physical Systems (CPS), Internet of Things (IoT), and Cloud Manufacturing (CM)) enable seamless communication and coordination between machines, opening up possibilities for highly customized and flexible production systems. With the increasing adoption of these technologies, industrial operations are projected to become up to 30% faster and 25% more efficient than conventional systems. Components and Enabling Technologies of Industry 4.0 According to Hermann et al. (2015), Industry 4.0 is built upon four foundational pillars: the Internet of Things (IoT), Cyber-Physical Systems (CPS), Cloud Manufacturing (CM), and Additive Manufacturing (AM), as well as Artificial Intelligence (AI). Beyond these, numerous additional technologies influence the modern supply chain landscape and may serve as sources of strategic differentiation. These include industrial automation, robotics, augmented reality, cybersecurity, blockchain, the "Internet of Data," semantic systems, advanced modelling tools, and next-generation network services (Lee et al., 2020). Shivaji et al. (2019) further emphasize that Industry 4.0 is underpinned by several conceptual elements such as transparency, digital modularization, decentralized decision-making, social collaboration, and mobile integration. Together, these features support continuous process monitoring and operational agility. What sets Industry 4.0 apart is its transformative impact on the structure and governance of industrial value networks. At the core of this transformation lies the widespread adoption of disruptive digital technologies (including cloud platforms, big data analytics, AI, blockchain, robotics, augmented reality, and simulation tools) across integrated production and distribution systems. To realize the full potential of these innovations, companies must align with several core design principles:

-Interoperability (systems can communicate effectively),
- Real-time capabilities (instantaneous data processing),
- Modularity (flexible configuration),
- Decentralization (autonomous decision-making), and
- Integrability (seamless system integration).

Collectively, these principles enable the emergence of an interconnected value creation environment (a hyper-connected, intelligent ecosystem in which data, technology, and human input coalesce to deliver more adaptive, efficient, and customer-centric outcomes) (Ghobakhloo et al., 2025).

2.2.1. Internet of Things (IoT)

The concept of the Internet of Things (IoT), which became prominent in the early 2000s, is a fundamental driver of Industry 4.0 (Hofmann & Rüsch, 2017). It establishes a seamless interaction between the physical and digital worlds by linking devices and sensors to enhance intelligence in products, services, and operations. IoT involves digital communication among systems that acquire real-world data via sensors. Key technologies enabling its growth include RFID, NFC, cloud computing, Wi-Fi, and cellular networks. According to Forrester Research, by 2020, global IoT revenue was projected to be 30 times greater than that of traditional Internet services. In various industries such as automotive, healthcare, and manufacturing, IoT supports logistics monitoring and addresses supply chain challenges through sensor-based data sharing (Jio et al., 2017). The Industrial Internet of Things (IIoT) serves as a critical technology for Industry 4.0, enabling connectivity between people, products, and processes via intelligent sensors and actuators. IIoT platforms allow companies to monitor equipment, analyze data, and improve operational efficiency, uptime, and cost-effectiveness (Maninder et al., 2020). By 2027, over 90% of IoT platforms are expected to feature digital twinning capabilities, which replicate physical systems in virtual environments for real-time analysis and optimization. Using sensors, IoT systems continuously gather and process data to create digital representations of physical objects. These models can be analyzed and simulated to predict performance and behavior. Organizations integrating digital twin technologies with IoT benefit from deeper insights and dynamic feedback loops. In Industry 4.0, such systems enable better machine status visibility, predictive analytics, scenario simulations, and behavior modeling (Attaran et al., 2024).

2.2.2. Cyber-Physical Systems (CPS)

Cyber-Physical Systems (CPS) are technological frameworks that seamlessly blend digital computation with physical processes through embedded control mechanisms. This integration empowers organizations to enhance how people interact with products and operations within the supply chain, resulting in improved flexibility and service performance. CPS serves as a central element in Industry 4.0, enabling real-time interaction between the virtual and tangible realms by combining computing, communication, and control layers. These systems are designed to enhance value creation by synchronizing physical functions with digital intelligence, thereby boosting competitiveness and operational efficiency. CPS is already being deployed across diverse industries, such as energy, finance, manufacturing, and transportation. For effective functioning, CPS comprises three fundamental layers:
- Network-connected smart devices
- Centralized or distributed application/information systems
- Cloud-based data storage and processing infrastructures (Harrison et al., 2021)

CPS forms one of the backbone technologies of the Fourth Industrial Revolution. Industry 4.0 emphasizes combining technological knowledge in ways that foster autonomy, consistency, and system-level control without constant human intervention. As noted by Zizic et al., the concept revolves around the creation of smart factories, where intelligent machines, storage units, products, and digital systems interact through cyber-physical production environments. Supporting technologies that operate in tandem with CPS include the Internet of Things (IoT), big data analytics, cloud platforms, and a range of smart automation tools. The fundamental purpose of CPS within Industry 4.0 is to align physical infrastructure with digital capabilities to enable superior productivity, streamlined automation, system interoperability, and enhanced operational design. Furthermore, Artificial Intelligence (AI) and CPS together represent powerful transformative forces in contemporary industrial evolution. However, current implementations of AI in CPS often lack interpretability, raising concerns in areas like ethics, legal accountability, regulation, and system transparency. This has led researchers such as Amber Hoegin et al. (2024) to emphasize the integration of Explainable AI (XAI) within CPS frameworks. Such integration is essential to ensure fairness, accountability, cybersecurity, safety, and robust system resilience.

2.2.3. Cloud Computing (CC)

Cloud Computing (CC) refers to delivering software applications and computing services over the internet, supported by data center infrastructure encompassing both hardware and software resources. Core components of CC include computational power, data analytics, network infrastructure, and scalable storage systems. These attributes grant the cloud exceptional advantages such as flexibility, geographical independence, scalability, and cost-efficiency (benefits that serve both service providers and users through virtually limitless access to computing resources) (Reza et al., 2019). Cloud platforms enable users to connect from any location through internet-enabled devices, empowering organizations to deploy services at scale. Within industrial settings, automation powered by cloud services has revolutionized operational workflows. Automated systems allow rapid task execution, improve productivity, and reduce the need for manual labor, leading to increased output and optimized resource allocation—including labor, materials, and equipment. In addition to operational agility, automation driven by cloud computing enhances quality management. For instance, real-time monitoring through embedded sensors and imaging systems ensures precise defect detection and guarantees that only high-standard products are delivered to customers, thereby reinforcing customer satisfaction and minimizing waste (Osinachi Deborah, Segun Falade et al., 2024).

2.2.4. Big Data (BD)

Big Data (BD) represents the aggregation of extensive and diverse datasets collected from both conventional and digital sources, allowing for continuous exploration and insight generation. It is commonly characterized by the "4Vs":
- Volume (massive scale of data),
- Variety (different data formats: text, images, audio, video, etc.),
- Veracity (data uncertainty or inconsistency), and
- Velocity (speed and frequency of data generation and transmission) (Isasi et al., 2018).

In today's intelligent manufacturing era, where IT is deeply integrated into industrial operations, enterprises are producing data at unprecedented scales. This influx of data supports organizations in precisely detecting internal and external changes, guiding informed decision-making, reducing costs, and improving operational efficiency. As a result, big industrial data acts not only as a source of insight but as a new factor of production, facilitating trends like mass customization and predictive marketing that drive socioeconomic growth. Moreover, the evolution of Artificial Intelligence has significantly boosted Big Data Analytics (BDA), enabling deeper extraction of value from both structured and unstructured data. In smart factories, continuous learning from vast datasets allows systems to adapt, optimize, and self-regulate. As BDA matures, it is expected to drive transformative changes in how industrial processes are planned, monitored, and executed (Junliang Wang et al., 2022).

2.2.5. Blockchain

Blockchain technology supports a wide array of applications by allowing multiple stakeholders to collaborate through shared platforms. A single blockchain infrastructure can facilitate diverse operational workflows, foster cross-organizational relationships, and accommodate various strategic objectives (Chunguang April Bai et al., 2024). What sets this technology apart is its decentralized, tamper-resistant, and auditable structure, enabling the secure sharing of digital ledgers. While commonly associated with cryptocurrencies, blockchain's application extends far beyond that. It relies on cryptographic hash functions and digital signatures to ensure data authenticity and synchronization across distributed systems. In supply chain contexts, blockchain can be integrated with Internet of Things (IoT) technologies to enable real-time tracking and monitoring. This enhances security, increases visibility, and improves resilience to cyber threats by identifying weak points within the chain. For instance, drones can be used to retrieve track-and-trace data from RFID-tagged items, improving traceability at various stages.

Notable characteristics of blockchain include:

- Decentralization: peer-to-peer transactions without the need for third-party mediation
- Trust & Provenance: irreversible validation mechanisms for tracking data origins
- Security & Immutability: confirmed transactions are resistant to tampering (Morabito, 2017)

Beyond supply chains, blockchain's potential spans finance, smart contracts, digital identities, loyalty programs, and regulatory compliance. Its benefits include increased transparency, reduced operational costs, faster transaction cycles, and broader access to financial services (especially in underserved regions) (O'Donnell, Richards, PwC & Plansky, 2018).

Forward-looking organizations can leverage blockchain to scale operations and maintain competitiveness. As more industries adopt it, blockchain is redefining traditional logistics and production systems, enabling new alliances between firms, external partners, and broader markets. This shift is paving the way for adaptive, innovation-driven industrial ecosystems (Chunguang April Bai et al., 2024).

2.2.6. Artificial Intelligence (AI)

Artificial Intelligence (AI) represents a pivotal branch of information technology that enables machines to make decisions independently and perform tasks typically requiring human input. Depending on the use case, AI can either operate as a full decision-making system or enhance individual processes. For example, a standard warehouse system might report inventory levels, while an AI-enabled smart warehouse can detect inefficiencies, analyze their causes, and implement solutions to improve supply chain performance. AI is an umbrella term encompassing a range of technologies (such as machine learning (ML), deep learning, neural networks, cognitive computing, and natural language processing (NLP)) that empower systems to learn, adapt, and act with increasing sophistication. Recent breakthroughs in AI have led to the development of high-performance models capable of uncovering complex patterns in large datasets. The term "learning" in this context refers to an algorithm's capacity to enhance its performance as it processes more data. Research in this area is advancing rapidly, especially in enhancing the transparency and interpretability of AI models. One emerging trend is automated machine learning (AutoML), which streamlines tasks like model selection, optimization, and training broadening AI accessibility. A particularly innovative subfield is (reinforcement learning), which relies on iterative simulation-based feedback. This technique has been instrumental in advancing applications like robotic control and decision-making in dynamic environments (Vincenzo Varriale et al., 2023).

2.3. Supply Chain 4.0

Traditional supply chains have historically followed the SCOR model, encompassing stages such as planning, sourcing, production, delivery, returns, and continuous improvement. With the advent of digital technologies, these processes are undergoing a major transformation. Today, Supply Chain 4.0 integrates modern tools across key functional domains including:

- Real-time logistics visibility
- Procurement 4.0 strategies
- Intelligent warehousing
- Unified planning and execution
- Spare parts optimization
- Autonomous logistics and direct-to-consumer (B2C) services
- Advanced analytical tools for supply chain insight
- Deployment of smart devices throughout the network

Digital transformation reshapes both organizational structures and business models, requiring cohesive collaboration between IT departments and operational units (Galindo, 2016). To fully leverage Industry 4.0 technologies, companies must foster strong collaboration among all members of the supply chain. This collaborative supply chain (SCC) becomes essential in adapting to rapid technological changes and managing the disruptions caused by inconsistent alignment with new market conditions. Industry 4.0 introduces complexities that challenge the seamless flow of supply chain operations making adaptability and coordinated responses a necessity for SC managers. Collaboration has thus become a core survival strategy for all actors within the modern supply chain. Evaluating collaborative performance under Industry 4.0 technologies is vital for establishing frameworks that enable effective inter-organizational cooperation. Knowing the dimensions and expected outcomes of such collaboration paves the way for SCC 4.0 implementation. The growing intensity of competition and shifting customer expectations demand faster, smarter responses from supply chain partners. Yet, current evidence suggests that collaboration often remains superficial business partners rarely co-develop initiatives or outsource secondary activities, leading to weak inter-firm integration. To overcome these gaps, a conceptual framework is needed one that can be utilized by all stakeholders, regardless of their role within the network. Technologies such as cloud computing have already demonstrated strong potential in facilitating SCC 4.0, improving inventory control, communication, and coordination between suppliers and retailers.

Effective collaboration in Supply Chain 4.0 revolves around activating multiple dimensions, including:

- Information and communication alignment
- Integrated resource and logistics planning
- Joint decision-making on strategic goals
- Innovation and business development
- Motivational and cultural cohesion
- Performance assessment across shared operations
- Market responsiveness and customer-centric orientation

When these elements work in harmony, organizations can achieve long-term, sustainable performance in a rapidly evolving commercial landscape (Aliahmadi et al., 2024). Factors Affecting the Performance of the Integrated Supply Chain a preliminary assessment of the key variables influencing supply chain performance allows us to categorize them into four overarching groups, based on thematic and functional similarities. These categories represent the diverse challenges organizations encounter while adopting Industry 4.0 technologies:

a) Technological factors

Encompassing the level of digital readiness, automation capabilities, system integration, and data processing infrastructures.

b) Financial, environmental, and legal factors

Covering cost-effectiveness, investment in innovation, sustainability regulations, compliance frameworks, and government incentives.

c) Socio-cultural factors

Including organizational culture, employee skillsets, and openness to innovation, inter-organizational trust, and cross-cultural collaboration norms.

d) Technical factors

Relating to the maturity of manufacturing systems, IT infrastructure resilience, operational standardization, and system interoperability across the value chain.

These categories reflect not only the internal complexities of implementing Industry 4.0 technologies but also the broader institutional and cultural readiness required to ensure successful supply chain integration in increasingly digitized environments.

2.4. Factors Affecting the Performance of the Integrated Supply Chain.

The initial analysis of the factors allows us to classify them into four distinct macro groups based on the similarities implied in their occurrence. Table 1 shows macro groups and their related factors. It summarizes the factors companies face and will face when implementing Industry 4.0 technologies in the supply chain.

a) Technological factors;
b) Financial, environmental and legal factors;
c) Socio-cultural factors;
d) Technical factors.

Table 1. Classification of supply chain factors 4.0 (Martinez, (2020))

Technical factors
1- high level of computer / computing requirements and strategies 2- Compatibility 3- Complexity 4- Reliability, strength and interoperability of systems 5- The challenge in storing, discovering and sharing data 6- Scalability 7- Security / privacy
Financial, environmental, legal factors
1- Environmental challenges 2- Financial investment 3- Standardization / legal policies
Technological factors
1- Different dynamics and time structures of production processes 2- Lack of initiative, skill and/or insufficient knowledge 3- Immature technologies
Cultural/social factors
1-Adaptation to new business models 2- Strategic alignment between functions, companies and governance 3- Cooperation of supply chain participants 4- Inability to combine data / obtain quality data 5- Fear of change 6- Human and technology relationship

2.6. A Reflection on Iran's Automotive Sector

The strategic role of the automotive industry in economic development has led many countries to heavily invest in this field. Through long-term commitment and investment, such countries have secured a significant global position in manufacturing, employment generation, and value creation. Iran's automobile sector, now over six decades old, has experienced a complex trajectory shaped by numerous fluctuations (Fereydoni et al., 2021). Currently, various external and internal factors such as exchange rate volatility, diversification in product and service offerings, shorter product life cycles, and market demand fluctuations, rising operational costs, rapid technological shifts, political uncertainties, economic instability, and even natural disasters have intensified uncertainty across the automotive supply chain. In addition, the broad structure of Iran's automotive supply network, involving numerous interdependent firms from raw material procurement to end-product delivery, presents considerable risk and complexity (Dehnavi et al., 2018). Meanwhile, the global move toward digital transformation has made it increasingly challenging Iranian carmakers to efficiently manage their supply chains through conventional methods. The adoption of Industry 4.0, by promoting sustainability and reducing direct human interaction with machinery, has become a pivotal approach for enhancing productivity and cutting costs (Dehnavi et al., 2017). Despite these benefits, the Iranian automotive sector has shown limited readiness to adopt such advancements. Critical shortcomings include insufficient emphasis on expanding engineering capabilities and inadequate alignment with global market expectations, particularly in product innovation and competitiveness (Mohammad et al., 2018). Notably, the automobile sector stands as one of the most impactful domains for implementing Industry 4.0 principles. Introducing and expanding cutting-edge technologies in production fosters a competitive edge. However, this shift requires not only strategic vision but also an in-depth understanding of essential infrastructural needs. Since Industry 4.0 is inherently tied to sustainability, grounded in economic, environmental, and social principles, realizing these goals necessitates broad economic restructuring (often referred to as the circular economy) operationalized through revised business models. Automotive firms have begun integrating new management strategies to reinforce sustainability across the production supply chain. In line with Iran's Vision 1404 document, national policies emphasize sustainable development across all sectors, including automotive manufacturing. Achieving this vision involves addressing basic human needs, raising living standards, safeguarding ecosystems, and promoting long-term societal well-being (Amir Ardehi et al., 2022).

From a technological standpoint, Wang (2016) identified key challenges in maintaining data quality across international supply chains. His study highlighted three IoT-based functions, monitoring and control, data analytics, and collaborative information sharing, as central, with data integration and standardization remaining major obstacles due to incompatible communication protocols and varied data management practices.

Similarly, Wu et al. (2016) examined intelligent supply chain systems, emphasizing gaps in technological application and the early-stage maturity of Supply Chain 4.0 frameworks.

In the healthcare sector, Al-Otaibi and Mahmoud (2017) underscored the importance of legal balance between digital suppliers and consumers a principle increasingly relevant for automotive ecosystems.

In another relevant study, Chen et al. (2017) addressed reliability and privacy issues within RFID and IoT systems, underlining the necessity of secure infrastructures when scaling up digitally connected platforms.

Finally, Bienhaus and Hadad (2018) explored how digital transformation affects supply and procurement practices. Their findings point to a growing need for procurement to evolve from operational execution toward a strategic function, supporting innovation, efficiency, and the creation of new business models.

3. Research Methodology

The choice of the research method depends on the objectives, the nature of the research subject, and the possibilities of its implementation. Management research methods are usually divided according to the purpose, data collection methods and nature of values. The research method is divided into primary and applied categories based on the objective. Based on the nature of the data, research methods can be divided into quantitative, qualitative, and mixed research (Hafez Niya, 2014). The present research is quantitative in terms of data nature. The current research is in the category of survey research and case studies because the central part of the information has been collected through questionnaires completed by specialists and experts in the field of study.

3.1. Research Variables

The evaluation framework of the research factors includes four stages, which are:

Step 1: Identifying factors affecting the performance of the integrated supply chain using Industry 4.0 technology in the automotive industry.

Step 2: Assessment of significance, weighting, and interdependence of factors, along with verification of judgment consistency and prioritization through the Fuzzy Analytic Network Process (ANP).

Step 3: Calculation of the effective weight of the indicators with the fuzzy ANP approach.

Step 4: Ranking the factors affecting the performance of the integrated supply chain using Industry 4.0 technology in the automotive industry and determining the final rank with the fuzzy ANP approach.

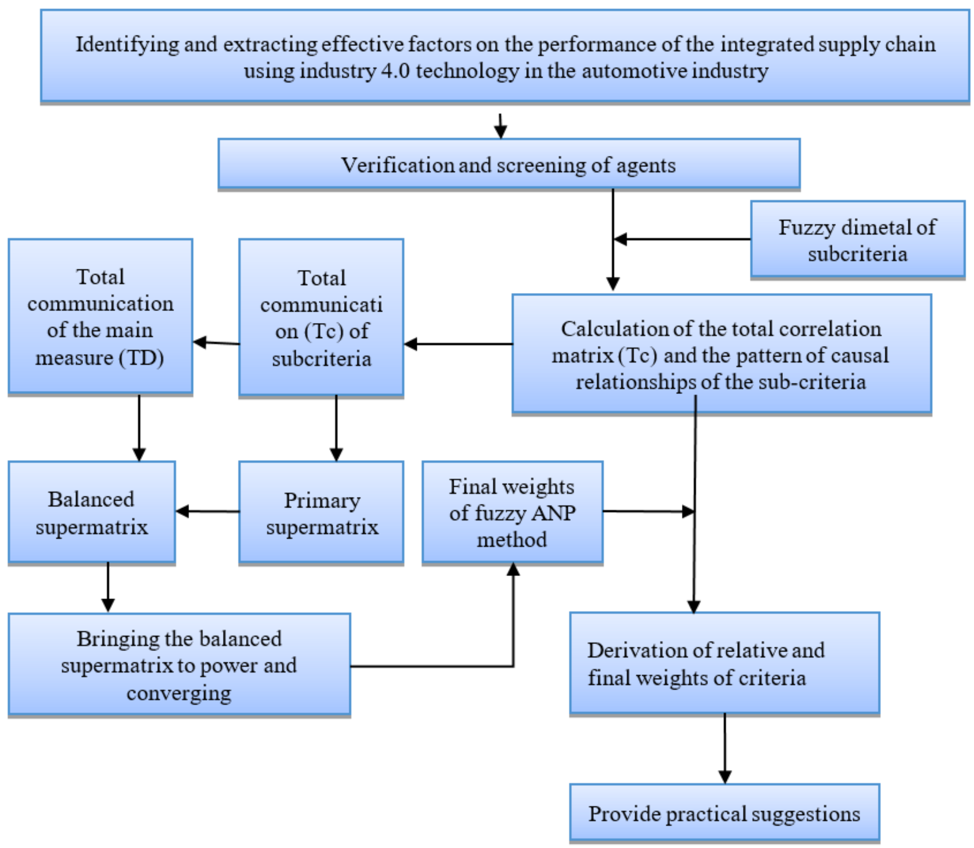

Figure 1. Research Method

3.2. Society and Statistical Sample

Scientific research seeks to analyze relationships among variables (typically formulated as hypotheses or research questions) within a defined statistical population. A statistical population comprises individuals or units sharing at least one common characteristic. A representative subset of this population is referred to as a sample (Rahimi, 2015). The statistical population in the present study consists of managers from automotive companies listed on the Tehran Stock Exchange. In the first stage, 75 individuals were considered, and using Morgan's table (Sekaran, 2003), an appropriate sample size of 63 participants was selected.

3.3. Data Collection Method

Two categories of data were utilized: primary and secondary sources (Rahimi, 2015).

Secondary Data: To explore the theoretical foundations and conduct a systematic literature review, data were collected through library research, including industrial books, journals, internet sources, and related studies. The researcher compiled articles from Scopus, Google Scholar, and Science databases, selecting peer-reviewed journal papers for review.

Primary Data: A researcher-developed questionnaire was used to collect primary data. Following a review of theoretical literature, a 31-item questionnaire was constructed and validated by field experts. Upon approval, it was distributed to respondents and later collected. A second questionnaire, using the DEMATEL Method, was completed by experts to assess interrelations among the studied factors. To verify content validity, the questionnaire was reviewed multiple times by specialists and faculty members. Drawing upon literature and expert insights, the final version was designed to assess factors influencing the performance of the integrated supply chain.

3.4. Validity and Reliability of the Questionnaire

To ensure the reliability of the first questionnaire (used for identifying and screening indicators) Cronbach's alpha was calculated. This statistic is widely accepted when its value exceeds 0.7. Using SPSS software, the reliability coefficient obtained was 0.73, confirming acceptable reliability for the instrument.

3.5. Data Analysis Method

This study employed a multi-criteria decision-making (MCDM) approach. Specifically, the fuzzy DEMATEL-ANP hybrid method was implemented, in which a fuzzy DEMATEL matrix informs the construction of a fuzzy ANP supermatrix. Computational steps (including solving matrices and constructing the supermatrix) were executed using Excel software. These matrices ultimately present the final analytical outcomes of the study.

3.6. ANP Method

The Analytic Network Process (ANP) is a multi-criteria decision-making technique used to assign weights to criteria and identify the optimal alternatives. While similar to the Analytic Hierarchy Process (AHP), ANP offers certain advantages:

1. It does not rely on a strictly hierarchical structure, allowing for more complex interrelationships among elements.

2. The second justification for using the ANP method lies in its capacity to account for the intricate relationships that are crucial in multivariate decision-making. Unlike AHP, the ANP technique does not rely on a strict hierarchical structure, allowing for a networked representation of decision levels. This structure facilitates the consideration of feedback and interdependencies between criteria and alternatives. The weights derived from causal relationships and the internal significance of each cluster form the initial supermatrix. This matrix is then normalized and processed in its limit form to generate the final priority weights of the elements.

Traditional management science relies on precise and deterministic data to evaluate complex issues. However, such approaches often fail to capture the nuance and subjectivity inherent in human thought. In response to this limitation, fuzzy logic principles were applied in this study. Lotfizadeh first introduced the concept of fuzzy sets, in which verbal variables (qualitative terms expressed in natural language) are quantified to resolve ambiguity and reflect expert intuition. These linguistic variables, though non-numerical in nature, can be transformed into numerical values using fuzzy set theory (Habibollah et al., 2019).

4. Data Analysis

Data analysis represents one of the most critical phases in any research. Errors in this stage may lead to misleading conclusions. Accordingly, this chapter presents a systematic analysis aimed at addressing the research objectives and questions. The relevant factors were initially identified and extracted, followed by their prioritization using the fuzzy DEMATEL–ANP method.

4.1. Introduction of Research Factors

Based on an extensive literature review and prior research, 31 factors were identified as influential in the performance of the integrated supply chain within the context of Industry 4.0 technologies in the automotive sector. To localize these factors, a survey was conducted using a 5-point Likert scale (1 = very low importance, 5 = very high importance) with 63 respondents. The average score for each item was computed; any item scoring below 3 was excluded. Table

2 presents the results of this evaluation. The final accepted criteria and their coded sub-criteria are presented in Table 3.

Table 2. Evaluation of research factors (Sorkheh et al., 2022)

Criteria	Under the Criteria	Average score
Technical	Computerization of processes	3.540
	Compatibility of system	2.905
	Complexity of systems	2.889
	Requirements and strategy of computing networks	3.889
	Reliability of systems	3.984
	Security and privacy of people	2.889
	Challenges of storage, discovery, and data sharing	3.810
	Robustness and interoperability of systems	2.937
	Innovative ability to develop and integrate new values	2.730
	Technical feasibility for technology implementation	2.952
Financial/Environmental/Legal	Environmental challenges	3.952
	Investment challenges	4.063
	Standardization	3.984
	Legislative policies	3.921
Sociocultural	New business models	3.905
	Fear of change	2.889
	Human relationship with technology	3.857
	Cooperation of participants	3.889
	Strategic alignment between tasks and companies and the government	2.857
	Inability to combine data and achieve quality data	3.905
	Replacement/expulsion of the human agent	2.984
Technological	Big data	3.968
	Cloud computing	2.921
	Internet of Things	2.968
	RFID tag and sensor systems and other integrating factors	2.778
	Digital transformation DX	3.810
	Digitization of the DSN supply network	2.937
	Different dynamics and temporal structures of the production process in the application of technology	2.841
	Lack of initiatives and skills	4.111
	Insufficient knowledge in the field of the fourth industry	3.968
	Immature technology	3.952

Table 3. Factors affecting the performance of the integrated supply chain in the context of Industry 4.0 technology in the automotive industry (Sorkheh et al., 2022)

	Standard code	Under the Criteria	Substandard code
Technical	A	Computerization of processes	A1
		Requirements and strategy of computing networks	A2
		Reliability of systems	A3
		Challenges of storage, discovery, and data sharing	A4
Financial/Environmental/Legal	B	Environmental challenges	B1
		Investment challenges	B2
		Standardization	B3
		Legislative policies	B4
Sociocultural	C	New business models	C1
		Human relationship with technology	C2
		Cooperation of participants	C3
		Inability to combine data and achieve quality data	C4
Technological	D	big data	D1
		Digital transformation DX	D2
		Lack of initiatives and skills	D3
		Insufficient knowledge in the field of the fourth industry	D4
		immature technology	D5

4.2. Fuzzy Dimatel-ANP (D-ANP)

The Fuzzy D-ANP technique represents a hybrid analytical framework that integrates the DEMATEL method with the Analytic Network Process (ANP). This methodology constructs ANP supermatrices based on the total communication (TC) matrix derived from DEMATEL and subsequently calculates the weights of the research indicators. The process includes the following sequential steps (Hu et al., 2015):

1- Calculation of direct correlation matrix (D)
2- Normalization of the direct correlation matrix
3- Calculation of the complete correlation matrix of criteria (TC)
4- Calculation of the complete correlation matrix of dimensions
5- Calculation of the pattern of causal relations of the TC matrix
6- Drawing a network relationship map (NRM)
7- Normalization of the full-dimension correlation matrix (T_D^∝)
8- Normalization of the complete correlation matrix of criteria (T_C^∝) and formation of an unbalanced supermatrix
9- Formation of balanced super matrix
10- Limiting the balanced super matrix.
11- Extraction of weights and prioritization of factors.

Table 4. Relative and final weights of factors (Sorkheh et al., 2022)

Criterion Name	Code	Final Weight
Technical	**A**	**0/27265**
Computerization of Processes	A1	0.06535
Requirements and Strategy of Computing Networks	A2	0.06434
Reliability of Systems	A3	0.06706
Challenges of Storage, Discovery, and Data Sharing	A4	0.07590
Financial/Environmental/Legal	**B**	**0/23088**
Environmental Challenges	B1	0.05252
Investment Challenges	B2	0.06273
Standardization	B3	0.06247
Legislative Policies	B4	0.05316
Sociocultural	**C**	**0/27935**
New Business Models	C1	0.07237
Human Relationship with Technology	C2	0.06730
Cooperation of Participants	C3	0.07160
Inability to Combine Data and Achieve Quality Qata	C4	0.06808
Technological	**D**	**0/21712**
Big Data	D1	0.04766
Digital Transformation DX	D2	0.04589
Lack of Initiatives and Skills	D3	0.03975
Insufficient knowledge in the Field of the Fourth Industry	D4	0.04058
Immature Technology	D5	0.04324

According to Table 4, among the main criteria, socio-cultural, with a weight of 0.27935, ranks first, and technical, with a weight of 0.27265, ranks second. Financial/environmental/legal, with a weight of 0.23088, has won third place and technological, with a weight of 0.21712, has won fourth place.

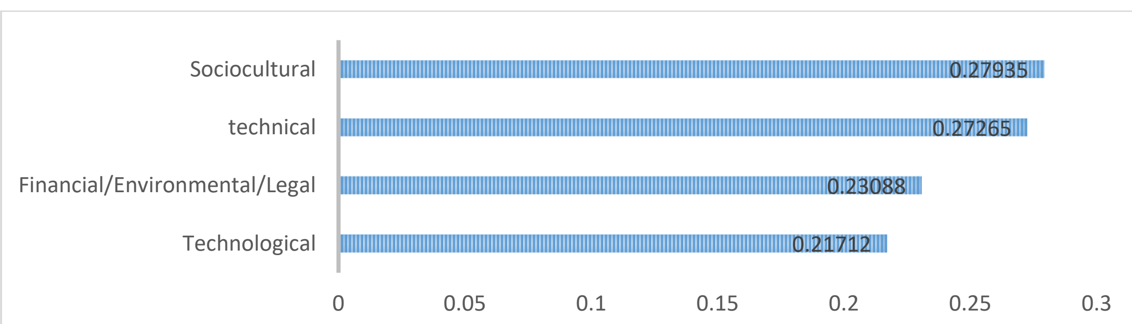

Figure 2. The weight of the main criteria (Sorkheh et al., 2022)

The ranking of the sub-criteria is based on the final weight in Table 4. Based on this, the challenges of storing, exploring, and sharing data weighing 0.0759 have won the first rank among 17 sub-criteria. New business models with a weight of 0.0724 won the second place and the cooperation of participants with a weight of 0.0716 won the third place.

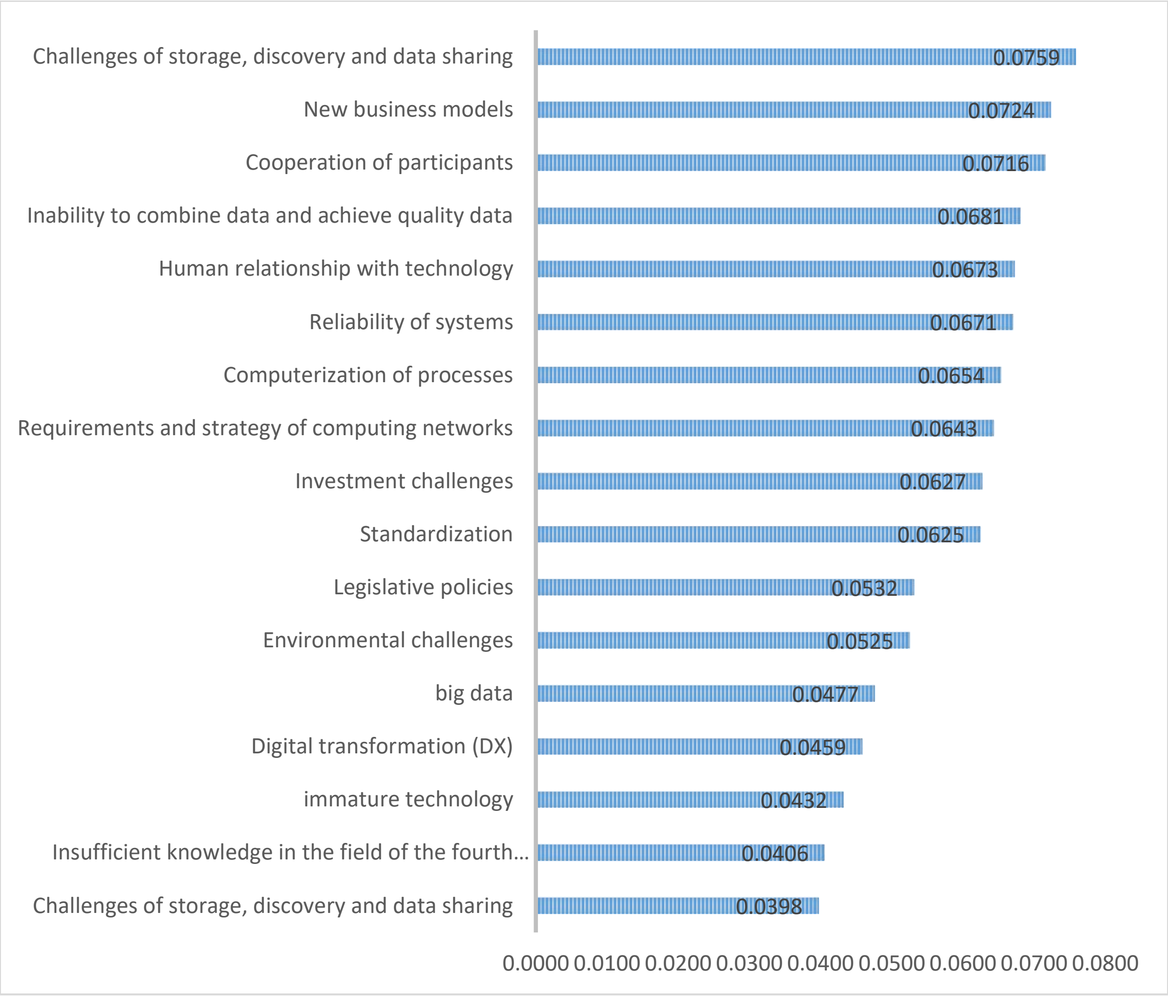

Figure 3. Weight and final ranking of sub-criteria (Sorkheh et al., 2022)

5. Conclusions and Suggestions

5.1. Results

In this section, the result of the research is presented by summarizing the findings of the previous sections to answer the main questions raised in the first section. Then, the results of this research were discussed, and at the end, suggestions were presented for managers and future researchers.

1- According to the findings, the influential criteria of this research that have the most impact (according to the obtained weights) are the social/cultural factors. Resistance to accepting and learning new technologies, ethical and safety issues, sharing the workspace with machines, replacing labor with technologies, Fear of applying intelligent users in the supply chain, and fear of change all are the things that cause the failure to properly implement new technology that improves the performance of the integrated supply chain. Finally, the organization can become digital when its employees become digital. Therefore, employees must be thoroughly trained in the new technology so that employees proficient in digital technology support the effects of the new technology.

2- According to the results of the data analysis, the cooperation of the participants of the supply chain of automotive companies indicates some problems that start with the adoption and mutual investment in fourth industry technology and extend to the difficulty in apportioning responsibility for mistakes in the digital realm.

3- The results showed that legal policies and rules to ensure the safety and integrity of people in this new environment (Industry 4.0), where humans and robots have a shared space and work collaboratively both inside and outside the company environment are required. In addition, international laws are needed to ensure security and privacy for problems related to personal injury and product liability in case of failure and sharing of information liability. The balance of legal obligations between infrastructure providers and customers in the digital world (Technology 4.0) is also essential.

4- According to the research, among the obstacles to the development of intelligent applications in the supply chain (Industry 4.0) is the lack of initiative, skills and knowledge in technology and the maturity of the concept of the supply chain and the initial stage of the development of the fourth supply chain which requires significant investments in this sector, which such investments to obtain data and services from this technology do not always provide financial returns.

5- According to the findings, problems such as data storage, analysis and processing using the traditional method are due to the volume in the variety and heterogeneity of the data. In addition, creating a system capable of interpreting and providing valuable information from data is complex and requires a strategy (4th industry technology) and a trained team, as well as an infrastructure capable of supporting all computing needs.

6- According to the findings of the research, the effective factors (sub-criteria), the lack of capacity to combine data and access to quality data, is one of the cultural/social challenges of the mega group that should be given more attention by companies, because of the different existing communication patterns and formats, different methods of collecting, storing and combining data, the lack of information technology specialists with adaptive knowledge (Industry 4.0) and the appropriate use of data and the problems of integrating data and systems and Also, their quality is a factor that prevents the use of data in its entirety, which brings little return from the use of Industry 4.0 technology.

7- According to the findings of the research, managers to the diversity of operational models and lack of integration between functions, the lack of governance structure of the supply chain, they pointed out the lack of strategy for using 4.0 technology and the lack of ability to adapt and integrate companies with this business model of Industry 4.0 technology.

5.2. Suggestions and Recommendation

1. Automotive companies should invest more substantially in digitalization and automation. Early adoption and full implementation can eliminate waste and enhance operational efficiency.

2. The digital transformation strategy must align with existing business models to foster innovation and collaborative culture. Process digitization (especially in procurement, logistics, cross-border trade) can drive financial performance and transparency.

3. Government involvement is essential to address legislative gaps.a lack of robust regulations may result in security vulnerabilities and systemic challenges.

4. Future corporate strategies should recognize the critical impact of these factors on integrated supply chain performance. Further investigation is recommended to support effective implementation of Industry 4.0 systems.

5. To harness big data, companies must focus on data relevance, predictive modeling, and process optimization to create value-driven organizational change.

6. Researchers are encouraged to examine evolving criteria and variables relevant to emerging industries when exploring supply chain integration strategies.

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