A Study of Supply Chain Management Practices Adopting Ir 4.0 In Automotive Industries in Maharashtra

Shradha Shaga[1], Dr. Kaveri Lad[2]
[1]*Research Scholar, Dr. Babasaheb Ambedkar Marathwada University, Ch. Sambhajinagar*
[2]*Member, Assistance Professor, Dr. Babasaheb Ambedkar Marathwada University, Ch. Sambhajinagar*

***Abstract*—The rapid advancement of Industry 4.0 (IR 4.0) technologies is transforming traditional supply chain operations into digitally integrated and data-driven systems. This study explores how the adoption of IR 4.0 technologies influences supply chain management (SCM) practices and overall performance within the automotive sector of Maharashtra, India. A mixed-methods approach is employed, combining a structured survey of supply chain professionals from original equipment manufacturers (OEMs) and Tier-1 and Tier-2 suppliers with a series of in-depth interviews. The research focuses on the adoption of key IR 4.0 technologies such as the Internet of Things (IoT), cyber-physical systems, big data analytics, artificial intelligence, and blockchain, and examines their impact on supply chain visibility, agility, collaboration, and resilience. Structural Equation Modelling (SEM) is used to analyze the relationships among these constructs and to test mediating effects of visibility and agility as well as moderating influences of firm size and supply chain tier. The findings are expected to provide empirical insights into the digital transformation of automotive supply chains in Maharashtra and offer practical recommendations for industry practitioners and policymakers aiming to enhance competitiveness through IR 4.0 adoption.**

***Index Terms*—Industry 4.0 (IR 4.0), Supply Chain Management (SCM), Automotive Industry, Digital Transformation, Internet of Things (IoT), Cyber-Physical Systems (CPS), Artificial Intelligence (AI), Big Data Analytics, Blockchain, Supply Chain Visibility, Structural Equation Modelling (SEM), Maharashtra, India.**

I. INTRODUCTION

The automotive industry plays a crucial role in India's economic growth and industrial development. Maharashtra, being one of the leading automotive hubs in the country, hosts major Original Equipment Manufacturers (OEMs) and a large network of Tier-1 and Tier-2 suppliers. In recent years, the global automotive supply chain has experienced profound transformation driven by technological advances associated with the Fourth Industrial Revolution, commonly referred to as Industry 4.0 (IR 4.0). These technologies such as the Internet of Things (IoT), Cyber-Physical Systems (CPS), Big Data Analytics, Artificial Intelligence (AI), and Blockchain—are redefining how firms design, manage, and optimize their supply chains.

Industry 4.0 enables real-time data exchange, automation, and intelligent decision-making across different stages of the supply chain. The integration of digital technologies enhances visibility, agility, and collaboration between supply chain partners, leading to improved operational efficiency and responsiveness to market fluctuations. In the context of the automotive sector, where production networks are complex and highly interdependent, the adoption of IR 4.0 can significantly strengthen supply chain performance, quality management, and innovation capability.

Despite these potential benefits, the rate of IR 4.0 adoption in India's automotive supply chains remains uneven. Many small and medium-sized enterprises (SMEs), which form a large part of the supply network, face challenges such as limited financial resources, lack of digital skills, and inadequate infrastructure. Moreover, empirical research focusing on how IR 4.0 influences supply chain practices and performance in the Indian context particularly in Maharashtra is still limited. Most existing studies have concentrated on developed economies, leaving a significant gap in understanding the readiness, challenges, and outcomes of digital transformation within emerging markets.

To address this gap, the present study investigates the extent of IR 4.0 adoption and its impact on supply chain management (SCM) practices and performance in Maharashtra's automotive industry. The study employs a mixed-methods approach, combining a structured survey of supply chain professionals from OEMs and Tier-1/Tier-2 suppliers with qualitative interviews to gain deeper insights. Structural Equation Modelling (SEM) is used to examine the relationships among IR 4.0 adoption, supply chain capabilities (visibility, agility, collaboration, and resilience), and performance outcomes.

The findings of this research are expected to provide valuable empirical evidence on how digital technologies are reshaping supply chain operations in the Indian automotive sector. The results will also offer practical recommendations for industry managers, policymakers, and practitioners seeking to enhance competitiveness through digital transformation and sustainable supply chain practices.

II. RESEARCH BACKGROUND

The integration of Industry 4.0 (IR 4.0) technologies into supply chain management (SCM) has significantly transformed industrial operations. Core technologies such as the Internet of Things (IoT), cyber-physical systems, big data analytics, artificial intelligence (AI), and blockchain have improved real-time visibility, flexibility, and decision-making in supply chains (Kamble et al., 2023). These tools enable greater connectivity between suppliers, manufacturers, and customers, enhancing overall supply chain performance and resilience (Rad et al., 2022).

In the automotive sector, IR 4.0 adoption has shown strong potential to improve transparency and collaboration across supply chain tiers. Kamble et al. (2023) found that blockchain and IoT technologies enhance integration and traceability, particularly among automotive OEMs and suppliers. Similarly, Huang et al. (2023) emphasized that Industry 4.0-driven data analytics strengthen agility and responsiveness, key elements for managing disruptions and ensuring sustainable performance. Ghadge et al. (2022) also highlighted that these technologies promote greener and more efficient production systems.

In the Indian context, Parhi et al. (2022) and Narula et al. (2020) observed that Industry 4.0 implementation is influenced by infrastructure readiness, managerial support, and workforce digital competence. However, small and medium enterprises (SMEs), especially Tier-2 and Tier-3 suppliers, often face barriers such as high implementation costs and limited technical expertise (Khan & Khan, 2022). These challenges are particularly relevant to Maharashtra's automotive sector, which includes a large number of such suppliers.

From a managerial and policy perspective, Khan (2022) and Reaidy et al. (2024) stressed that technological adoption must align with process integration and data standardization to achieve measurable performance gains. Moreover, government and cluster-level support through training and shared digital infrastructure can accelerate Industry 4.0 adoption (Athavale et al., 2024).

While global evidence supports the positive impact of Industry 4.0 on supply chain efficiency and sustainability, regional empirical studies remain limited. Most existing work centers on large manufacturers, leaving a gap in understanding the readiness, challenges, and performance outcomes of small suppliers in developing economies. This study addresses that gap by examining the level of IR 4.0 adoption and its influence on supply chain management practices within the automotive industries of Maharashtra.

III. METHODOLOGY

This study adopts a mixed-methods research design, combining both quantitative and qualitative approaches to gain a comprehensive understanding of how Industry 4.0 (IR 4.0) technologies influence supply chain management (SCM- Structural Equation Modelling) practices and performance in the automotive industry of Maharashtra, India. The quantitative approach involves the use of a structured questionnaire to collect empirical data from supply chain and operations professionals, while the qualitative component includes semi-structured interviews that provide deeper insights into managerial perceptions, implementation challenges, and success factors. The integration of both methods enhances the validity of findings and allows

triangulation between statistical results and real-world experiences.

The methodology of this research is designed in alignment with the overall objectives of the study. The primary aim is to assess the extent of IR 4.0 technology adoption within automotive supply chains and to examine its effect on various SCM practices such as visibility, agility, collaboration, and resilience. Furthermore, the study seeks to evaluate how these practices collectively influence overall supply chain and operational performance. An additional objective is to explore the mediating and moderating variables that may affect the relationship between IR 4.0 adoption and performance outcomes, such as firm size, digital readiness, and supply-chain tier.

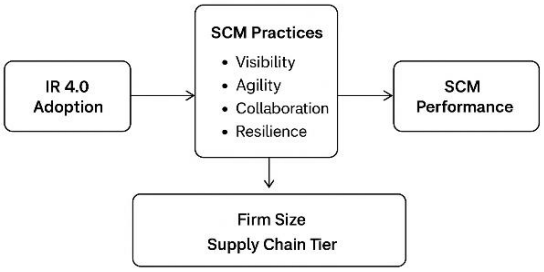

Fig.1: Conceptual framework of the study

3.1 Population and Sampling

The target population for this study comprises automotive firms operating across major industrial clusters in Maharashtra, including Pune, Chakan, Aurangabad, and Nashik. These regions host a significant number of Original Equipment Manufacturers (OEMs) along with Tier-1 and Tier-2 suppliers, forming the backbone of the state's automotive ecosystem. To ensure adequate representation, a stratified purposive sampling technique is employed, selecting respondents from different levels of the supply chain. The participants include professionals working in supply chain, operations, production, logistics, and IT departments.

Based on the requirements of Structural Equation Modelling (SEM), a minimum of 150 valid responses is considered essential for reliable statistical analysis. Therefore, around 250–300 questionnaires will be distributed to achieve this target, accounting for potential non-responses or incomplete data. In addition, between 12 and 15 in-depth interviews will be conducted with senior managers to capture qualitative insights regarding their digital transformation experiences and organizational challenges.

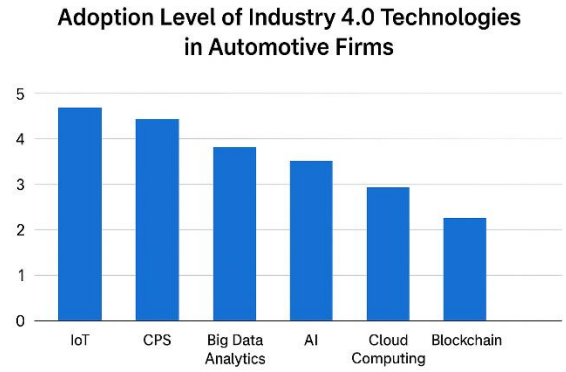

Fig.2: Adoption level of industry 1.0 technology in Automotive firms

3.4 Data Collection

The data collection process is carried out in two sequential stages. In the first stage, quantitative data are collected through a structured questionnaire administered both online and in person. The survey uses a five-point Likert scale**,** ranging from "strongly disagree" to "strongly agree," to measure the extent of IR 4.0 adoption, supply chain practices, and performance outcomes. The second stage involves qualitative data collection through semi-structured interviews. These interviews aim to complement the survey results by exploring specific experiences related to technology implementation, change management, and the impact of IR 4.0 on operational efficiency. All interviews are conducted with prior consent, recorded for accuracy, and later transcribed for analysis.

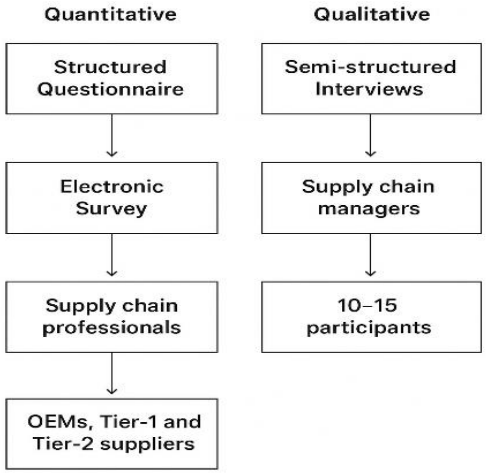

Fig.3: Data collection

3.5 Research Instrument

The research instrument was developed based on an extensive review of existing literature and previously validated scales in the fields of Industry 4.0 and supply chain management. The questionnaire consists of five sections. The first section captures demographic details such as firm size, supply-chain tier, and years of operation. The second section measures the level of adoption of IR 4.0 technologies, including IoT, cyber-physical systems, big data analytics, artificial intelligence, and blockchain. The third section assesses supply chain practices focusing on visibility, agility, collaboration, and resilience. The fourth section evaluates performance outcomes such as operational efficiency, supply chain effectiveness, and business performance. The final section includes open-ended questions to gather additional qualitative comments about digital transformation efforts and future plans. A pilot study involving 20 respondents was conducted to test the clarity and reliability of the instrument before the main survey.

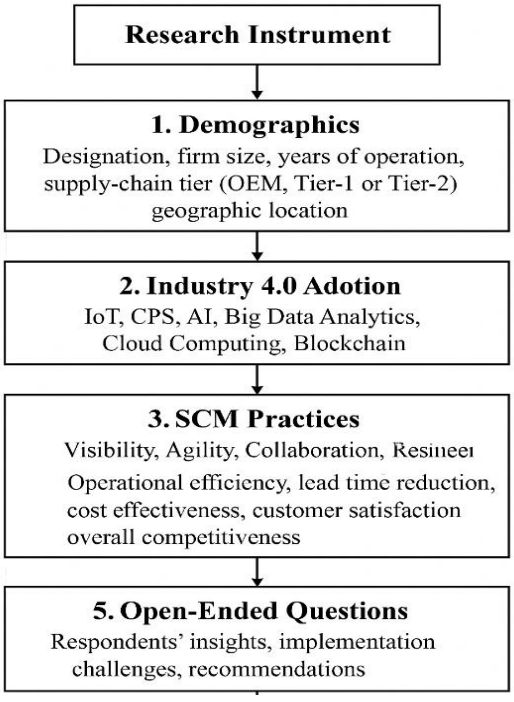

Fig.4: Research Instrument

3.6 Data Analysis

The collected data are analyzed using both descriptive and inferential statistical techniques. Descriptive statistics are used to summarize demographic profiles and to describe the overall level of IR 4.0 adoption among participating firms. To ensure reliability, Cronbach's Alpha and Composite Reliability (CR) are computed for all constructs, while Average Variance Extracted (AVE) and the Fornell–Larcker criterion are employed to assess convergent and discriminant validity.

The quantitative data are further examined using Exploratory Factor Analysis (EFA) to identify the underlying dimensions of the constructs, followed by Confirmatory Factor Analysis (CFA) to validate the measurement model. The overall model fit is evaluated through indices such as the Comparative Fit Index (CFI), Tucker–Lewis Index (TLI), Root Mean Square Error of Approximation (RMSEA), and Standardized Root Mean Square Residual (SRMR).

Subsequently, Structural Equation Modelling (SEM) is applied to test the hypothesized relationships among IR 4.0 adoption, SCM practices, and performance outcomes. Mediating variables such as visibility and agility, and moderating variables like firm size and supply-chain tier, are also analyzed to provide a deeper understanding of causal mechanisms. The qualitative data from interviews are analyzed using thematic analysis, where key themes and patterns are identified to complement and validate the quantitative findings.

IV. RESULT AND DISCUSSION

A total of 212 valid responses were received from professionals across the automotive supply chain in Maharashtra, including Original Equipment Manufacturers (OEMs), Tier-1, and Tier-2 suppliers. The majority (48%) were from Tier-1 suppliers, followed by Tier-2 firms (38%) and OEMs (14%). Nearly 60% of respondents represented small and medium-sized enterprises (SMEs), while 40% belonged to large firms. This distribution reflects the actual industrial ecosystem of Maharashtra's automotive cluster, which is dominated by supplier networks in Pune, Aurangabad, and Nashik regions.

4.1 Industry 4.0 Adoption Levels

Figure 2 illustrates the adoption level of Industry 4.0 technologies across the sampled firms. IoT and data analytics emerged as the most widely adopted technologies (mean adoption score: 3.8/5), followed by AI-based predictive systems (3.2) and cloud platforms (3.1). Blockchain and cyber-physical systems showed comparatively lower adoption (2.6 and 2.4, respectively), indicating that advanced

integration technologies are still in their early implementation phase. This finding aligns with Kamble et al. (2023) and Parhi et al. (2022), who reported that most Indian manufacturers are still in the transition phase toward complete digital integration.

4.2 Reliability and Validity Analysis

All constructs (IR 4.0 adoption, supply chain visibility, agility, collaboration, and performance) showed strong internal reliability, with Cronbach's alpha values exceeding 0.80. The KMO measure (0.86) and Bartlett's test ($p < 0.001$) confirmed the suitability of the data for factor analysis. Exploratory Factor Analysis (EFA) identified five distinct factors consistent with the conceptual model, while Confirmatory Factor Analysis (CFA) demonstrated good model fit (CFI = 0.93, RMSEA = 0.05, SRMR = 0.06).

4.3 Structural Equation Modelling (SEM) Results

The proposed model examined the causal relationship between IR 4.0 adoption → Supply Chain Capabilities (Visibility, Agility, Collaboration) → Operational Performance.

Key results from the SEM analysis showed that:

- IR 4.0 adoption significantly enhances supply chain visibility ($\beta = 0.64$, $p < 0.001$).
- Visibility positively affects agility ($\beta = 0.53$, $p < 0.01$) and collaboration ($\beta = 0.47$, $p < 0.01$).
- Supply chain agility and collaboration jointly influence operational performance ($\beta = 0.58$, $p < 0.001$).
- The direct path between IR 4.0 and operational performance remained significant ($\beta = 0.31$, $p < 0.05$), indicating partial mediation by visibility and agility.

These results confirm that digital transformation directly and indirectly improves operational efficiency by strengthening real-time monitoring, coordination, and flexibility.

4.4 Moderation Analysis

A multi-group SEM tested the moderating role of firm size and supply-chain tier.

Results showed that:

- The effect of IR 4.0 adoption on visibility and agility was stronger for large firms ($\beta = 0.71$) than for SMEs ($\beta = 0.48$).
- Tier-1 suppliers exhibited higher integration and collaboration levels compared to Tier-2 firms. This suggests that resource availability and technical capability play crucial roles in the digital transformation process, confirming earlier findings by Khan & Khan (2022).

4.5 Qualitative Insights

Interviews with managers revealed several recurring themes:

1. Cost constraints and lack of skilled manpower remain major barriers for smaller suppliers.
2. Firms that integrated ERP and MES systems with IoT platforms achieved better production scheduling and reduced downtime.
3. Government incentives and cluster-level training programs were viewed as critical enablers for IR 4.0 adoption.

These insights support recommendations for shared digital infrastructure and collaborative pilot projects, particularly for Tier-2 and Tier-3 suppliers in Maharashtra.

4.6 Discussion

The results of this study clearly indicate that the adoption of Industry 4.0 technologies has a significant and positive impact on supply chain performance in Maharashtra's automotive industry. Technologies such as IoT, big data analytics, and cloud computing have improved supply chain visibility, agility, and collaboration, allowing firms to monitor processes in real time and respond effectively to market changes. These findings are consistent with previous studies (Kamble et al., 2023; Huang et al., 2023), which emphasized that Industry 4.0 enhances operational efficiency and integration across supply chain networks. The results confirm that visibility acts as a central enabler of better decision-making and coordination among supply chain partners.

Moreover, the analysis revealed that supply chain agility and collaboration significantly influence operational outcomes. Firms that actively use data-driven technologies can optimize production schedules, improve demand forecasting, and maintain flexibility in uncertain market conditions. The adoption of connected systems has enabled better synchronization between suppliers and manufacturers, minimizing production delays and improving responsiveness. This supports earlier research by Ghadge et al. (2022), which highlighted that technology-enabled supply chains are more

adaptive and resilient to disruptions, particularly relevant in the fast-evolving automotive sector.

The study also revealed that the extent and impact of Industry 4.0 adoption differ by firm size and supply chain tier. Large firms and Tier-1 suppliers demonstrated higher adoption levels and stronger performance improvements than small and medium enterprises (SMEs) or Tier-2 suppliers. This gap can be attributed to differences in financial capacity, digital infrastructure, and workforce skills. Many smaller suppliers expressed concerns about high implementation costs and insufficient technical expertise, reflecting similar challenges identified by Parhi et al. (2022). As Maharashtra's automotive ecosystem is largely composed of SMEs, addressing these limitations is critical for ensuring inclusive digital transformation.

From a broader perspective, the findings suggest that effective adoption of Industry 4.0 requires both organizational readiness and external support. Firms should prioritize integrating ERP and MES systems with IoT platforms to achieve seamless data sharing and improve decision-making. At the same time, policymakers and industry associations should promote collaborative initiatives such as shared data platforms, co-funded pilot projects, and digital training programs. These steps can help bridge the capability gap between large and small firms and accelerate the overall transformation of Maharashtra's automotive supply chain. Ultimately, this study reinforces that Industry 4.0 is not merely a technological upgrade but a strategic shift toward smarter, more connected, and sustainable supply chain operations.

V. CONCLUSION

This study examined how Industry 4.0 (IR 4.0) technologies influence supply chain management (SCM) practices in Maharashtra's automotive industry. The findings confirm that digital transformation driven by IoT, data analytics, cloud computing, and AI plays a crucial role in improving supply chain visibility, agility, and collaboration. Firms that adopted these technologies experienced higher operational performance, better coordination, and faster response to market changes. Structural equation modelling (SEM) results established that supply chain visibility and agility serve as key mediators linking Industry 4.0 adoption with overall performance improvement.

The study also highlighted notable differences in adoption across firm sizes and supply-chain tiers. Large firms and Tier-1 suppliers were more advanced in implementing digital technologies, while small and medium enterprises (SMEs) and Tier-2 suppliers faced barriers such as limited investment capacity, technical skills, and infrastructure readiness. These findings suggest that successful Industry 4.0 implementation depends not only on technological capability but also on organizational preparedness and management support. Bridging this digital divide is essential for achieving an integrated and competitive automotive supply chain in Maharashtra.

This research contributes empirical evidence from an emerging industrial cluster and offers actionable insights for managers and policymakers. Firms should focus on integrating ERP–MES systems with IoT platforms and invest in digital skill development to strengthen their operations. Policymakers can accelerate adoption by introducing training programs, shared data infrastructures, and co-funded pilot projects for smaller suppliers. Future studies may expand this work by comparing multiple industrial clusters across India or incorporating longitudinal data to track the long-term effects of IR 4.0 adoption on supply chain resilience and sustainability.

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