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# Integration of Lean Supply Chain and Industry 4.0

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## Abstract

In response to the dynamic and highly competitive business environment, incorporating additional ideas and tools alongside lean supply chain implementation has become essential. One emerging trend is the integration of a Lean Supply Chain with Industry 4.0, which aligns with the core principles of lean, including cost reduction, waste elimination, and improved supply chain efficiency. This research aims to investigate the relationship between Lean Supply Chain and Industry 4.0 technologies and explore their mutual interactions. The Interpretative Structured Modelling (ISM) methodology will be employed to gain a comprehensive understanding of their interdependencies. By bridging the existing gap in the literature, this study provides valuable insights for both researchers and practitioners, enabling them to navigate the direction and implications of integrating Lean Supply Chain and Industry 4.0.

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## 1. Introduction

During the 1990s, companies adopted innovative operational strategies such as Lean Manufacturing to address the dynamic nature of customer demands and the complexities of a globalized business landscape. In response to the inadequacy of internal efficiency within competitive supply chains, companies have redirected their attention towards supplier collaboration, acknowledging the necessity of cooperative efforts to meet customer demands. The emergence of the "Lean Supply Chain" concept has brought forth a set of comprehensive principles extending throughout the entirety of the supply chain. This comprehensive application establishes a value stream encompassing individuals,

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functions, and operationally synchronized entities, all operating in harmony to create, manage, and deliver customer value while minimizing inefficiencies and optimizing effectiveness. Throughout the years, a significant amount of scholarly and practical research has been conducted on Lean Supply Chains, with a particular focus on exploring their impact on the field of supply chain management.

Current scholarly investigations have extensively explored the practical ramifications, constraints, and advantages of Lean Supply Chains, bolstered by empirical analyses that authenticate systematic approaches. The scope of this exploration has been broadened to incorporate wider business themes, such as the triple bottom line concept. Concurrently, the emergence of Industry 4.0 has brought about significant transformations in technological, organizational, and managerial dimensions within companies, specifically concerning the digitalization of supply chains. This study aims to investigate the interactions between Lean Supply Chain principles and Industry 4.0, as both approaches share a common objective of utilizing technology to improve efficiency and minimize waste. Nevertheless, a limited amount of literature is available that thoroughly examines the synergies between these paradigms, as it primarily consists of fragmented inquiries and diverse viewpoints. To bridge this existing knowledge gap, our objective is to comprehensively analyze the various applications and challenges associated with Industry 4.0 and Lean Supply Chain. This analysis will provide valuable insights into the intricate relationship between these two concepts.

This study aims to examine the complex relationship between Lean Supply Chain (LSC) and Industry 4.0 practices, focusing on understanding how their integration can enhance operational efficiency and create synergistic effects. The subsequent literature review presents an overview of the various applications and challenges linked to implementing Lean Supply Chain and Industry 4.0. This systematic review comprehensively analyzes these paradigms, formulating a research question addressing the identified knowledge gap. Utilizing the Interpretive Structural Modeling (ISM) methodology, the study systematically delineates its aims, procedural stages, and the corresponding merits and demerits. The subsequent theoretical framework elaborates on the methodology utilized, emphasizing its efficacy in substantiating findings, particularly considering the originality of the subject matter and its alignment with prior scholarly works.

## 2. Literature Review

In the ever-evolving business landscape, the pursuit of flexibility and cost reduction has driven the adoption of Lean Thinking, a pivotal tool for optimizing production efficiency through waste reduction and Just-In Time practices, providing a competitive edge [1], [2]. However, as supply chain competition intensifies, the focus on single-company efficiency has shifted towards the crucial realm of supply chain efficiency for maintaining competitiveness. Organizations have embraced Lean Supply Chain practices to bolster efficiency, competitiveness, and overall performance. However, the current business milieu has illuminated the limitations of Lean Thinking within the supply chain, necessitating the integration of complementary concepts and tools. The applicability of Lean Supply Chain spans diverse contexts such as the triple bottom line (3BL), small and medium-sized enterprises (SMEs), globalization, and Industry 4.0 [3], [4]. This study delves into the integration of Lean Supply Chain and Industry 4.0, meticulously examining their practices and uncovering the symbiotic relationship where Lean Supply Chain supports Industry 4.0, ultimately enhancing overall business outcomes. The research embarks with an in-depth literature review of Lean Supply Chain and Industry 4.0, employing Interpretative Structured Modelling (ISM), and subsequently undertakes a systematic literature review to unveil the intricate interplay and dependencies between these two paradigms.

### 2.1. Lean Supply Chain

In the dynamic market landscape, companies face the challenge of meeting customer expectations amid volatility [5], [6]. Scholars like Frohlich & Westbrook [7] and Krajewski et al. [8] highlight the success of integrating internal improvement processes with external stakeholders. Collaboration between suppliers and customers enhances competitiveness [9]. Pérez et al. [1] emphasize integration with key stakeholders, while Cox et al. [10] advocate collaborative supply chain engagement. Waste reduction and sustainability emphasize the importance of efficient supply chain management, where Lean Production (LP) based on TPS principles comes into play.

LP techniques have been adopted in supply chain management and product development to counter competitive pressures and meet demands [11]. The Lean Supply Chain (LSC) represents a network of organizations aiming to

reduce waste and meet customer requirements through coordinated products, services, and information [12]. LSCs excel in optimizing downstream value. Sectors like hospitality, healthcare, and retail benefit from Lean management [13], [14]. However, there's limited understanding of LSC activities upstream and downstream [15], [16], [17]. Downstream Lean practices need more attention [18], [19]. Barriers such as Heijunka and market variability hinder downstream Lean adoption. Focusing on first-tier manufacturers limits the establishment of sustainability throughout the chain.

The evolution of Lean principles extends from the plant floor to the optimization of the value chain [11]. Lean supply chain management (LSCM) combines Lean practices to create high-quality production systems aligned with customer demands [19]. LSCM enhances performance across organizations [20]. It necessitates a collaborative business model that values partnerships and waste elimination. LSCM calls for comprehensive SCM practices that synergize with Lean principles. Jasti and Kodali [16] propose an insightful eight-pillar, 82-element LSCM framework for supply chain enhancement. These pillars encompass leadership, IT management, supplier management, standardized processes, JIT production, customer management, logistics, and continuous improvement. Implementing these pillars enhances supply chain performance and fosters sustainability. They provide valuable guidance for effectively implementing LSCM and enhancing supply chain operations.

## 2.2. *Industry 4.0*

In 2011, the German Industry-Science Research Alliance introduced Industry 4.0, igniting the Fourth Industrial Revolution by digitally transforming manufacturing. Industry 4.0 seamlessly weaves digitalization into the supply chain, enabling real-time data exchange across entities, objects, and systems [21], [22]. This connectivity empowers AI-driven products, machines, and processes to dynamically adapt to changing environmental conditions [23]. The essence of Industry 4.0 lies in integrating ICT into industrial operations, merging smart products with digital and physical processes alongside value chain technologies [24]. Uniquely, Industry 4.0's impact transcends traditional digitization, reaching into business models, services, and organizational structures, catalyzing transformative shifts in society, education, and the labor landscape.

Industry 4.0 bestows a spectrum of benefits, encompassing superior decision-making, elevated productivity, enhanced quality, waste minimization, energy efficiency, and advocacy for sustainable manufacturing practices [25]. It also augments production scheduling, capacity utilization, energy management, and maintenance practices. Successful implementation hinges on balancing technical feasibility, societal acceptance, alignment with consumer needs, socio-economic adjustments, and the advancement of technological capabilities [26]. Embracing Industry 4.0 empowers businesses to enhance their competitive edge, adapt fluidly to evolving consumer expectations, adeptly manage the accelerated product life cycles, and amplify product diversity. Beyond this, Industry 4.0 fosters streamlining, automation, creation of high-skill jobs, and decentralization of workflows. While heralding transformation, policymakers must navigate the evolving technological landscape, and socio-economic adaptations are pivotal for achieving holistic societal progress. A comprehensive approach ensures enduring success and a positive societal imprint. Industry 4.0 emerges as a catalytic force, digitizing and propelling manufacturing to unprecedented heights, amplifying productivity, sustainability, and overall competitiveness. Effective Industry 4.0 integration pivots on meticulous consideration of technological feasibility, social acceptability, and continuous enhancement of workforce skills. Despite potential challenges, Industry 4.0 propels digital transformation, fueling innovation and efficiency across industrial domains, affording benefits to companies and societies alike.

## 2.3. *Lean Supply Chain and Industry 4.0*

The potential integration of Lean principles and Industry 4.0 holds promise alongside challenges. Bittencourt et al. [27] underscore that automation could hinder compatibility between waste-reduction tech and Lean setups. Merging Lean and Industry 4.0 has the potential to reduce costs and bolster productivity. Saxby et al. [28] emphasize the need for standardization, organization, and transparency to align Industry 4.0 with Lean. They also stress Lean system maturity's importance in Industry 4.0 [28]. Haddud and Khare [29] illustrate how digitalized supply chains impact Lean Supply Chains (LSCs), transforming practices like JIT, VMI, TPM, CI, and Poka-Yoke. The integration of digital tech and information exchange supports Industry 4.0 and LSCM, enhancing flexibility, coordination, and

customer satisfaction [30]. Sanders et al. [31] propose that Industry 4.0 complements Lean by diversifying tasks and engaging workers.

Effective amalgamation of Lean Supply Chains and Industry 4.0 necessitates a coordinated external and internal ICT framework. Ward and Zhou [32] and Jasti and Kodali [16] stress the importance of IT management and information dissemination. Lean manufacturing harnesses digital transformation for waste reduction and seamless supply chain integration, as highlighted by Ashrafian et al. [33]. Ensuring that Lean practices align with tech while maintaining the organizational culture is vital. Successful integration hinges on compatibility and a strategic focus on cultural alignment. Huang et al. [34], Costa et al. [35], Chiarini et al. [36], Thürer et al. [37], and Rossini et al. [38] underscore continuous improvement, innovation, and learning for synergies. Chiarini [36] suggests optimizing Lean before introducing Industry 4.0. Prioritizing training, change management, and the strategic fusion of Lean and Industry 4.0 advances efficiency, productivity, and customer experience while considering culture and tech optimization.

### 3. Methodology

This study section focuses on thoroughly examining the complex relationship between Lean Supply Chain and Industry 4.0. The primary aim is to comprehensively examine the practices that produce substantial results when successfully executed. These practices can yield significant advantages by optimizing their individual outcomes and promoting the adoption of complementary practices within the interconnected domains of Lean Supply Chain and Industry 4.0. In order to achieve this objective, a methodology that combines Interpretive Structural Modeling (ISM) and MICMAC analysis is utilized to elucidate the intricate network of relationships within and between these paradigms. The inquiry is driven by data from an extensive survey and a group of experts in the field. The individuals in question have been assigned the responsibility of assessing the effects of each practice, assigning ratings on a numerical scale that spans from 1 (representing minimal impact) to 5 (representing a substantial degree of influence). The data collected from a group of thirteen experts is meticulously gathered and subjected to rigorous standards to guarantee the results' dependability and precision. During this procedure, a thorough assessment is carried out, identifying and eliminating five responses that exhibited inadequacy or miscomprehension. Implementing a rigorous data validation procedure is crucial for ensuring the overall excellence of the research and preserving the integrity and credibility of the resulting conclusions.

The ISM methodology is crucial in facilitating a comprehensive understanding of the interrelationships between Lean Supply Chain and Industry 4.0. The utilization of ISM facilitates elucidating the underlying dynamics that govern the interactions among practices by systematically charting the relationships and hierarchies between them. This methodology enables the identification of practices that exert the most significant influence and offers valuable insights into their interrelationships. The primary methodology employed in this study is ISM, supplemented by other research methods and data sources to ensure a comprehensive and rigorous investigation of the subject matter. Integrating various methodologies enhances the dependability and comprehensiveness of the insights obtained from this research endeavor.

### 4. Result and Discussion

#### 4.1. Interpretive Structural Modeling (ISM) Procedure

This section provides a detailed description of the ISM procedure utilized to study the links between Lean Supply Chain (LSC) and Industry 4.0 (I4.0) and presents an analysis of the results.

**Step 1: Identification of Significant Structural Interaction Matrices (SSIM)** - The insights from eligible experts were collected and then aggregated to generate a consolidated matrix for analytical purposes. Subsequently, a specific threshold was determined to derive the Structural Similarity Index (SSIM). This threshold value, 3.6, was established in consultation with experts. For the analysis, values falling below this threshold are considered less relevant. This does not indicate a lack of correlation but signifies a relatively weaker degree of correlation. After completing this

process, the Structural Self-Interaction Matrix was constructed by transforming the values obtained from V, A, X, and O based on their contextual relationships.:

- V indicates that practice i influences practice j, implying that the implementation of practice j would benefit from practice i.
- A indicates that practice i is influenced by practice j, meaning that the implementation of practice i would benefit from practice j.
- X indicates that practices i and j mutually influence each other, signifying that adopting each practice would benefit the other.
- O indicates that the practices are unrelated.

**Step 2: Development of Initial Reachability Matrix (RM)** - The ISM then converts the Structural Self-Interaction Matrix (SSIM) into the initial Reachability Matrix (RM). The methodology calls for replacing V, A, X, and O with binary numbers.

**Step 3: Development of the Final Reachability Matrix (RM)** - Adding 1\* entries to the initial Reachability Matrix incorporates the transitivity principle. This generates the Reachability Matrix. Consider P1-P9's relationship. P1 indirectly influences P3 because P9 influences P3. Thus, 1\* fills the cell at P1-P3 intersection.

**Step 4: Construction of the Conical Matrix for MICMAC Analysis** - This step is crucial for conducting the MICMAC analysis. It involves calculating and ranking each practice's driving and dependence power in descending order.

**Step 5: Level Partitioning** - Level partitioning determines the hierarchical model and practice levels. They identified each practice's reachability, antecedent, and intersection sets. Practices with identical reachability and intersection sets are at the top of the ISM hierarchy, indicating that they do not affect other factors. After removing the top-level factor, the process is repeated to determine each practice's level.

Table 1 - Level partitioning

First iteration				
	Reachability	Antecedent	Intersection	Level
P1	1,2,3,5,6,7,8,9,10,11,13,15	1,2,3,5,6,7,8,9,10,11,13,15	1,2,3,5,6,7,8,9,10,11,13,15	I
P2	1,2,3,5,6,7,8,9,10,11,13,15	1,2,3,5,6,7,8,9,10,11,13,15,18,20	1,2,3,5,6,7,8,9,10,11,13,15	I
P3	1,2,3,5,6,7,9,10,11,13	1,2,3,5,6,7,9,10,13	1,2,3,5,6,7,9,10,13	
P4	4,14,16,18,19,20	4	4	
P5	1,2,3,5,6,7,9,10,11,13,15	1,2,3,5,6,7,8,9,10,11,13,15	1,2,3,5,6,7,9,10,11,13,15	I
P6	1,2,3,5,6,7,8,9,10,11,13,15	1,2,3,5,6,7,8,9,10,11,13	1,2,3,5,6,7,8,9,10,11,13	
P7	1,2,3,5,6,7,8,9,10,11,15	1,2,3,5,6,7,8,9,10,11,13	1,2,3,5,6,7,8,9,10,11	
P8	1,2,5,6,7,8,9,10,11,15	1,2,6,7,8,9,10,11,13,15	1,2,6,7,8,9,10,11,15	
P9	1,2,3,5,6,7,8,9,10,11,12,13,15	1,2,3,5,6,7,8,9,10,11,13,15	1,2,3,5,6,7,8,9,10,11,13,15	
P10	1,2,3,5,6,7,8,9,10,11,13,15	1,2,3,5,6,7,8,9,10,11,13	1,2,3,5,6,7,8,9,10,11,13	
P11	1,2,5,6,7,8,9,10,11	1,2,3,5,6,7,8,9,10,11,13	1,2,5,6,7,8,9,10,11	I
P12	12	9,12,13	12	I
P13	1,2,3,5,6,7,8,9,10,11,12,13,15	1,2,3,5,6,9,10,13	1,2,3,5,6,9,10,13	
P14	14,15,16,18,19,20,22	4,14,15,16,18,19,20,22	14,15,16,18,19,20,22	I
P15	1,2,5,8,9,14,15,16,18,21,22	1,2,5,6,7,8,9,10,13,14,15,16,18,19,20,22	1,2,5,8,9,14,15,16,18,22	
P16	14,15,16,18,20,21,22	4,14,15,16,18,19,20,22	14,15,16,18,20,22	
P17	17	17	17	I
P18	2,14,15,16,18,19,20,21,22	4,14,15,16,18,19,20,22	14,15,16,18,19,20,22	
P19	14,15,16,18,19,20,22	4,14,18,19,20,22	14,18,19,20,22	
P20	2,14,15,16,18,19,20,22	4,14,16,18,19,20,22	14,16,18,19,20,22	
P21	21	15,16,18,21,22	21	I
P22	14,15,16,18,19,20,21,22	14,15,16,18,19,20,22	14,15,16,18,19,20,22	
Second iteration				
	Reachability	Antecedent	Intersection	Level
P3	3,6,7,9,10,13	3,6,7,9,10,13	3,6,7,9,10,13	II

P4	4,16,18,19,20	4	4	
P6	3,6,7,8,9,10,13,15	3,6,7,8,9,10,13	3,6,7,8,9,10,13	
P7	3,6,7,8,9,10,15	3,6,7,8,9,10,13	3,6,7,8,9,10	
P8	6,7,8,9,10,15	6,7,8,9,10,13,15	6,7,8,9,10,15	II
P9	3,6,7,8,9,10,13,15	3,6,7,8,9,10,13,15	3,6,7,8,9,10,13,15	II
P10	3,6,7,8,9,10,13,15	3,6,7,8,9,10,13	3,6,7,8,9,10,13	
P13	3,6,7,8,9,10,13,15	3,6,9,10,13	3,6,9,10,13	
P15	8,9,15,16,18,22	6,7,8,9,10,13,15,16,18,19,20,22	8,9,15,16,18,22	II
P16	15,16,18,20,22	4,15,16,18,19,20,22	15,16,18,20,22	II
P18	15,16,18,19,20,22	4,15,16,18,19,20,22	15,16,18,19,20,22	II
P19	15,16,18,19,20,22	4,18,19,20,22	18,19,20,22	
P20	15,16,18,19,20,22	4,16,18,19,20,22	16,18,19,20,22	
P22	15,16,18,19,20,22	15,16,18,19,20,22	15,16,18,19,20,22	II
<b>Third iteration</b>				
	<b>Reachability</b>	<b>Antecedent</b>	<b>Intersection</b>	<b>Level</b>
P4	4,19,20	4	4	
P6	6,7,10,13	6,7,10,13	6,7,10,13	III
P7	6,7,10	6,7,10,13	6,7,10	III
P10	6,7,10,13	6,7,10,13	6,7,10,13	III
P13	6,7,10,13	6,10,13	6,10,13	
P19	19,20	4,19,20	19,20	III
P20	19,20	4,19,20	19,20	III
<b>Fourth iteration</b>				
	<b>Reachability</b>	<b>Antecedent</b>	<b>Intersection</b>	<b>Level</b>
P4	4	4	4	IV
P13	13	13	13	IV

**Step 6: Development of Digraph** - Level partitioning creates the initial node-edge digraph. Eliminating indirect links yields the digraph. The digraph structure shows the practices' priority. In particular, lower digraph practices are more important than upper ones.

**Step 7: Development of ISM Model** - The culmination of the process involves constructing the ISM model by replacing the nodes of the practices in the digraph with corresponding statements. This representation is depicted in Figure 1 - ISM model.

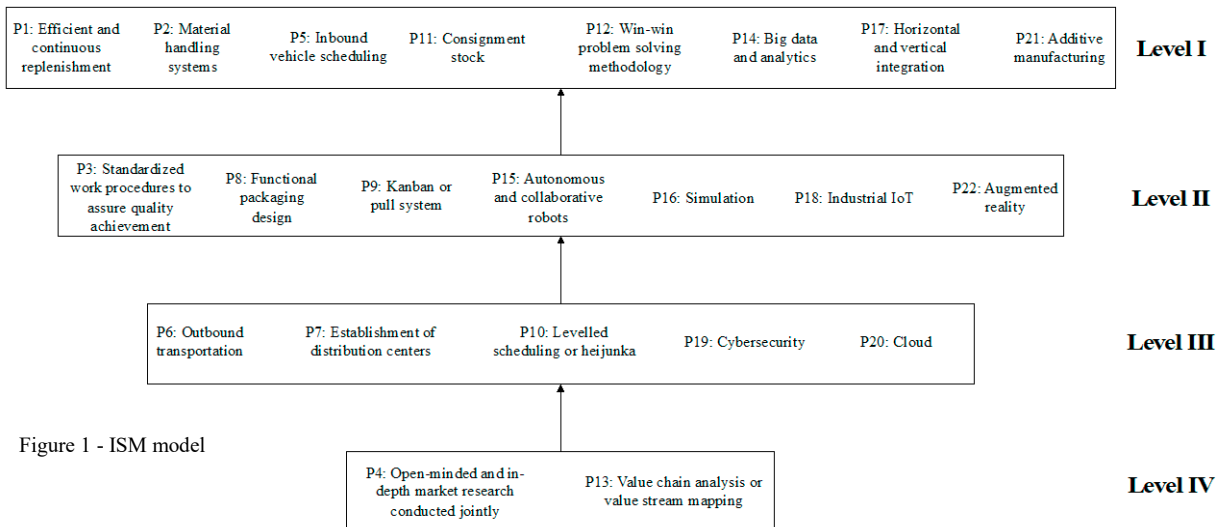


Figure 1 - ISM model

#### 4.2. Procedure: MICMAC analysis

The MICMAC analysis investigated indirect relationships among practices. Based on driving and dependence power values from ISM Step 4, practices were plotted on a diagram with dependence power on the x-axis and driving power on the y-axis. The diagram was divided into four groups using lines at 11, half the practices (22) considered. The clusters were as follows (Figure 2 - MICMAC):

- Autonomous practices (Cluster I): These include Standardized work procedures for quality (P3), Joint market research (P4), Functional packaging design (P8), Win-win problem-solving (P12), Big data analytics (P14), Simulation (P16), and more.
- No practices were classified as dependent (Cluster II).
- Linkage practices (Cluster III): This group has Efficient replenishment (P1), Material handling (P2), and Kanban system (P9).
- Independent practices (Cluster IV): Value chain analysis (P13).

Initially, some practices didn't fit specific quadrants. For instance, Consignment stock (P11) lies between Autonomous and Dependent clusters. Inbound vehicle scheduling (P5) and Autonomous and collaborative robots (P15) were between Linkage and Dependent clusters. Outbound transportation (P6) and Leveled scheduling (P10) were between Independent and Linkage clusters. The distribution center setup (P7) was at the diagram's center. Thus, further analysis was done to categorize these practices accurately.

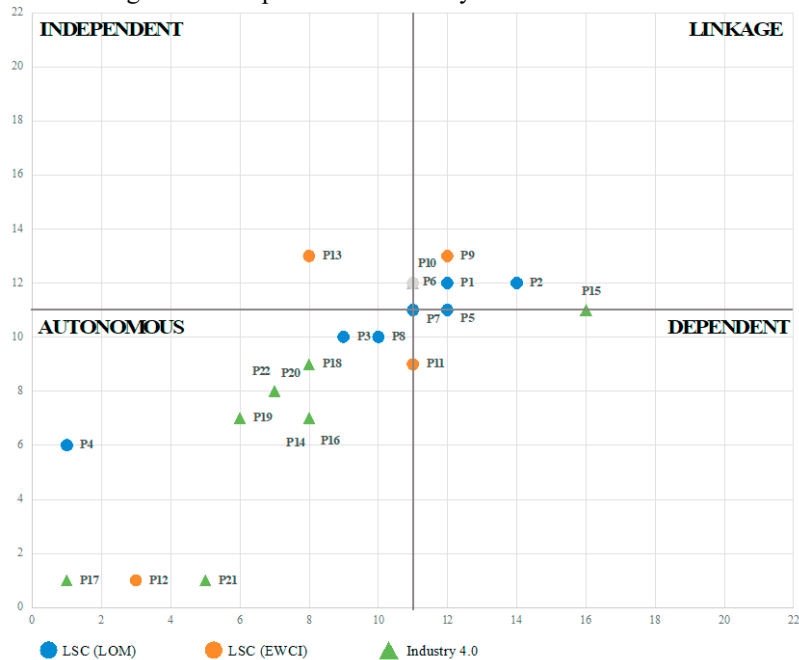


Figure 2 - MICMAC

#### 4.3. Results analysis: MICMAC

The system's data and relationships were examined using MICMAC analysis to avoid making assumptions about impact. All 22 practices were scrutinized for connections. The quadrant with low driving and dependence power displayed fewer interconnections but more practices and relationships. P12, P17, and P21 lacked systemic relationships. Open-minded and in-depth market research (P4) influenced specific practices, while quality-standard work procedures (P3) were constrained by the system. The quadrant with low driving and high dependence power included boundary practices, not specific ones. Consignment stock (P11) used Lean Supply Chain (LSC) methods, while inbound vehicle scheduling (P5) and autonomous and collaborative robots (P15) were Linkage and Dependent

quadrants with stronger incoming ties. Practices can be divided into linkage practices, more influenced than influential, and independent quadrant practices, high-driving yet low-dependent. The kanban or pull system (P9) impacts other practices, while essential independent quadrant practices like value chain analysis (P13), outbound transportation (P6), and leveled scheduling (P10) benefit the system. Distribution centers (P7) balance interactions among LSC practices, while autonomous and collaborative robots (P15) bridge LSC and Industry 4.0. Prioritizing practices in the Autonomous quadrant (e.g., big data analytics (P14), simulation (P16), Industrial IoT (P18), cybersecurity (P19), cloud (P20), and augmented reality (P22)) is important. Open-minded and in-depth market research (P4) is crucial due to null dependence and driving power. While informative, these findings need integration into a more comprehensive analysis to clearly understand practices' system impact. A comprehensive analysis is needed to understand practice impact for informed decisions. MICMAC sheds light on systemic practice dynamics, showing how autonomous, less connected, dependent, linkage, and independent variables affect practices. Understanding interactions and power aids practice prioritization for action plans and further research.

#### 4.4. Results analysis: ISM

This analysis uses the ISM model to explore Lean Supply Chain (LSC) and Industry 4.0 practices, revealing key connections. At Level IV, joint open-minded market research (P4) and value chain analysis (P13) emerge as significant. Prioritizing these practices is vital as they benefit others, with value chain analysis (P13) being self-sufficient and joint research (P4) influencing multiple practices. Cloud storage and big data analytics support research (P4), aiding Industry 4.0 adoption. Value chain analysis (P13) aids process mapping, efficient replenishment, material handling, and location optimization. Level III includes outbound transportation (P6), distribution center setup (P7), leveled scheduling (P10), cybersecurity (P19), and cloud (P20). Outbound transportation (P6) and leveled scheduling (P10) have high driving power and medium dependence, appearing in Level III. The distribution center setup (P7) matches its moderate influence and dependence. Cybersecurity (P19) and cloud (P20) are autonomous with high impact, placed at Level III due to their dependence on joint research (P4). Practices such as outbound transportation (P6) aid packaging and robots, while leveled scheduling (P10) improves planning. Distribution centers (P7) benefit from leveled scheduling (P10).

At Level II, practices supporting Lean-Industry 4.0 integration include quality work procedures (P3), packaging design (P8), kanban (P9), robots (P15), simulation (P16), industrial IoT (P18), and augmented reality (P22). Standardized work (P3), packaging design (P8), simulation (P16), IoT (P18), and augmented reality (P22) are autonomous, while kanban (P9) has influence (Linkage). These practices enhance replenishment, material handling, decision-making, and robot learning. Level I involves replenishment, material handling, inbound scheduling, consignment stock, win-win solving, big data analytics, integration (horizontal and vertical), and additive manufacturing. Efficient replenishment (P1) and material handling (P2) are in Level I (Linkage). Inbound scheduling (P5) is Level I Dependent. Consignment stock (P11) is semi-autonomous, while practices like win-win solving (P12), big data (P14), integration (P17), and additive manufacturing (P21) are autonomous. Horizontal and vertical integration (P17) has minimal impact, win-win solving (P12) and additive manufacturing (P21) can benefit from higher-level practices, and big data (P14) is moderately connected. The ISM analysis highlights the impact of joint research (P4) and value chain analysis (P13) on LSC practices. These guide supply chain design and operational planning; thus, prioritizing joint research (P4) can enhance Industry 4.0. Value chain analysis (P13) primarily aids LSC practices. Industry 4.0 supports LSC operations, especially Logistics Management (LOM) practices. Autonomous robots (P15) closely align with LSC and Industry 4.0.

## 5. Conclusion and Future Research

Thorough investigations were carried out to delve into the intricate relationship between Lean Supply Chain (LSC) and Industry 4.0, originally perceived as separate paradigms. This highlighted the essentiality of strategically implementing specific approaches from both frameworks to yield harmonious outcomes. A meticulous analysis of interactions pinpointed pivotal practices that facilitate cross-paradigm collaboration. However, the presence of intricate intra-paradigm connections complicated the interpretation of results. Within the domain of Industry 4.0, conventional practices like value chain analysis and value stream mapping, previously deemed relevant within isolated

paradigms, have now been augmented by the prominence of open-minded and comprehensive market research. This underscores the pressing need to cultivate inter-paradigm cohesion within Industry 4.0. Notably, within Industry 4.0, the integration of cybersecurity and cloud practices with LSC was lacking. Conversely, using autonomous and collaborative robots has surged in Industry 4.0, particularly when interwoven with Lean Supply Chain (LSC) practices. These robots have proven instrumental in enhancing the cross-paradigm dynamics in the industry. On the other hand, the practices harnessed by LSC exhibited limited linkages, especially in additive manufacturing, suggesting constrained influence and benefits within the broader system.

To dissect the interplay between Lean Six Sigma (LSC) and Industry 4.0, the Information Systems Management (ISM) methodology was harnessed. This process revealed specific practices that wield significant influence within each framework, serving as catalysts for integration and augmenting outcomes. Noteworthy practices that exhibited notable influence included joint market research (P4) and value chain analysis/value stream mapping (P13) for LSC. For Industry 4.0, autonomous/collaborative robots (P15), cybersecurity (P19), and cloud (P20) were identified as influential practices. Notably, both paradigms demonstrated externalities in P13, P19, and P20, while mutual benefits were observed between P4 and P15. Conversely, additive manufacturing (P21) displayed limited impact and advantages due to integration complexities.

This analysis effectively bridges an existing gap in literature and holds substantial implications for researchers and practitioners alike. Integrating Lean Six Sigma (LSC) methodologies with Industry 4.0 presents the potential for diverse advantages, ranging from enhanced operational efficiency and cost reduction to fortified competitive positioning. Businesses can elevate their processes and agility by prioritizing collaborative market research endeavors and embracing advanced robotics technology. Practitioners keen on implementing these concepts can benefit by channeling resources towards establishing dedicated market research teams and adopting cutting-edge robotics advancements. The study's findings underscore the pivotal role of these strategies in achieving seamless integration and favorable organizational outcomes. These initial insights provide a solid foundation for deeper exploration of Lean Supply Chain and Industry 4.0, offering a trajectory for theoretical advancement. Integrating methodologies like DEMATEL, ISM, and IRP, which embrace diverse expert perspectives, can substantially enhance the robustness and credibility of upcoming research ventures. Focused case studies within Lean Supply Chain and Industry 4.0 can validate theoretical insights and elucidate practical implications. Given the dynamic nature of this field, periodic analyses are advisable to stay attuned to evolving trends and maintain current knowledge.

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