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Revolutionizing Supply Chains: Unleashing Reconfigurability and Flexibility through Industry 4.0 Integration

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Abstract*– In response to dynamic market demands, supply chains are undergoing a transformative shift towards heightened flexibility through the reconfiguration of manufacturing processes. Industry 4.0 has emerged as a pivotal avenue for companies seeking to expedite this transformative journey. Nevertheless, the precise role of Industry 4.0 in enhancing the reconfigurability of manufacturing systems remains an evolving area of investigation. This study presents a comprehensive examination of Industry 4.0's impact on supply chain reconfigurability and flexibility. By pinpointing crucial dimensions of manufacturing system reconfigurability that enhance supply chain flexibility, we delve into empirical insights drawn from a robust study involving 309 High-Performance Manufacturing (HPM) project companies spanning 14 countries. Employing rigorous statistical mediation models and hierarchical regression analysis, each research hypothesis underwent thorough testing. The analysis of gathered data showcased commendable reliability levels. Our findings underscore that the identified reconfigurability dimensions significantly contribute to over 45% of observed flexibility within the supply chain. Notably, this relationship is partially influenced by the adoption and implementation of Industry 4.0 technologies, strategies, and tools.

Keywords: flexibility, reconfigurability, high performance, supply chain, Industry 4.0.

I. Introduction

The concept of flexibility in supply chain management has been a fixture since the 1980s, evolving to meet the demands of mass customization and adaptability to shifting products, production technologies, and market dynamics [1]. This period has witnessed sustained research into manufacturing flexibility, focusing on its taxonomy, core attributes, system frameworks, and incremental enhancements [2]. The overarching goal has been to enhance the seamless integration of critical business processes spanning from end-users to material suppliers, product manufacturers, service providers, and information stakeholders, thereby creating value for companies, customers, and stakeholders alike [3].

Central to these supply chain evolutions has been the drive to elevate customer satisfaction levels, thereby securing new avenues of competitive advantage infused with customer-centric value propositions [4]. As time progresses, this imperative has only intensified, with companies' competitiveness increasingly contingent upon their capacity to navigate market disruptions swiftly and profitably [5]. Often, these disruptions are inevitable, compelling companies to embrace measures that cultivate resilience and foster rapid adaptability to market shifts—essentially, enhancing their flexibility [6].

The prevailing market turbulence underscores the imperative for supply chains to be not only flexible but also reconfigurable, capable of promptly aligning with evolving market requirements. There exists a pressing need to augment the capacity for swift and profitable reorganization in response to real-time demands [7].

Changes in supply chains must be able to react as markets change. These must change or modify with the same speed as the market to compete effectively. Also, they must be flexible and alter or assume different positions quickly [8]. The Supply Chain flexibility is the ability to reconfigure and adapt to market requirements, the ability to increase the level of supplier response, and the network coordinator's ability to integrate the supply chain [9].

Therefore, supply chain reconfigurability is the ability to modify its configuration to respond to new customer requirements. There is a high relationship between reconfiguration and flexibility [5]. To achieve reconfiguration and flexibility, companies require the inclusion of techniques and tools from the fourth industrial revolution, called Industry 4.0, whose application has shown that it contributes to the reconfiguration and flexibility of the SC through its technologies, generating more transparency. , traceability, product customization, increasing flexibility, knowing customer demands, creating value, and even detecting new services [10].

Despite the above, there is scarce literature that evaluates how Industry 4.0 contributes to the reconfigurability of the supply chain to improve its flexibility and operational performance; it has received proper attention [11], given the disruptive changes that are taking place throughout the supply chain [12]. The research aim is to evaluate the role that Industry 4.0 has in the reconfigurability, and flexibility of the supply chain based on its essential characteristics: modularity, scalability, integrability, convertibility, diagnosability, and customization.

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Also, we aim to identify the current level of reconfigurability, and flexibility evidenced by companies to identify those with high performance over those with medium and low performance. We provide retrospective information for prospective decision-making that allows companies to boost their competitiveness until they reach a high-performance level. In this sense, we organize the document as follows: The second section addresses a specialized literature review, and the third section details the methodology used to resolve the research assumptions. The fourth section shows the results of the study. Finally, we present the conclusions and future research with the implications of this study for professionals and academia.

II. Literature review

A. *Defining SC flexibility, Reconfigurability*

Manufacturing and supply chain reconfigurability have been addressed since the last decade of the 20th century with the arrival of dedicated manufacturing lines and flexible manufacturing systems [13]. It has recently reconfigured its supply chains in response to new market trends. Companies require reconfigurability to ensure supply chain flexibility, agility, resilience, and viability. Supply chain reconfigurability is defined as a flexible chain capable of changing its structure with the minimum number of resources, guaranteeing the company's competitiveness in the market [14].

Also, reconfigurability is a cost-effectively designed, responsive, sustainable, and resilient network, increasingly data-driven and dynamically adaptive, capable of rapid structural changes in physical and cyber spaces by reorganizing and reallocating or changing its components to quickly adjust supply and production capabilities and functionality in response to sudden changes. Supply chain reconfigurability includes SC Agility, Lean SC, SC Digitalization, SC Sustainability, and SC Resilience [15]. In manufacturing, system reconfigurability involves a rapid change in structure to adjust production capacity and functionality in response to sudden changes in manufacturing requirements [16]. Nowadays, given the need to react quickly to the market, reconfigurability allows us to respond in an agile, accelerated, and efficient way to frequent market changes [13].

Six fundamental characteristics underpin reconfigurability: Modularity, Integrability, Personalization, Convertibility, Scalability, and Diagnosis [16]. Each of these traits offers unique avenues for flexibility, leveraging distinct development approaches, capabilities, and technologies within the supply chain [11]. The process of supply chain reconfiguration entails the adjustment of manufacturing processes, specifically the reconfiguration of machines by manipulating their configurable components. These components, often referred to as modules, are interchangeable elements that facilitate the performance of various functionalities when swapped between machines [17]. Reconfigurability demands hardware and software that can adapt and integrate quickly and reliably [16]. Reconfigurability implies two main aims: (1) reduce preparation time for launching new systems and reconfiguring existing systems, and (2) rapid manufacturing modification and rapid integration of new technologies and new functions into existing systems using core process modules (hardware and software) that would be reorganized quickly and reliably [8]. Reconfigurability articulates flexible manufacturing systems (FMS) and dedicated manufacturing systems [11].

B. *Reconfigurability and Industry 4.0*

There are more than 100 definitions of Industry 4.0 (I4.0), but there still needs to be a consensus [18]. I4.0 is a set of technologies that allow the connection and communication of objects in real-time, increasing the flexibility of the supply chain. Industry 4.0 improves capabilities related to developing new products, creation and development of prototypes, predictive maintenance, services and diagnostics, traceability, innovation, planning, agility, flexibility, and adaptability [19]. Over time, the application of Industry 4.0 in SC has made it possible to personalize products, increase flexibility, understand customer demands, constantly create value, and even detect new services [10]. Technologies that have potentially affected SC KPIs are: Virtual and augmented reality, Additive manufacturing, 3D printing, Simulation, Big data analytics, Cloud technology, Cybersecurity, Internet of things, Miniaturization of electronics, Automatic identification, and data collection (AIDC), Radio Frequency Identification (RFID), Robotics, Drones and Nanotechnology, Machine to Machine Communication (M2M) and Business Intelligence (BI) [10]. Nowadays, reconfiguration processes rely heavily on applying and aligning techniques, tools, and objectives derived from Industry 4.0 [19]. Industry 4.0 reduces operating costs while increasing flexibility through the technologies it comprises [11].

Industry 4.0 increases the supply chain's flexibility, reconfigurability, and intelligence [20]. Manufacturing digitalization plays a crucial role and is critical to the future of supply chains and manufacturing. As such, it focused on nine key technologies: advanced manufacturing solutions, additive manufacturing, augmented reality, simulation, vertical integration, horizontal, industrial internet, the cloud, cybersecurity, big data, and analysis. Industry 4.0 is an integrating factor and an enhancer of the supply chain reconfigurability, moving from mass production to personalized production. Industry 4.0 includes different technologies applied throughout operations, ranging from artificial intelligence, robotics, and digital technologies, which are applied at the floor level and to the networks of organizations. The achievement of flexibility in supply chains is based, among other things, on digital transformations, being considered a key element in achieving flexibility and reconfigurability of operations [21]. With the arrival of Industry 4.0, new opportunities emerge to improve organizations' Flexibility [12] continuously. Based on the arguments presented in the literature review, the research hypothesizes.

H1: Supply chain flexibility improves when Industry 4.0 is applied strategically in the manufacturing Reconfigurability.

H2: Industry 4.0 contributes positively and significantly to the supply chain Flexibility.
H3: Industry 4.0 contributes positively and significantly to the supply chain's reconfigurability.
H4: Reconfigurability and Industry 4.0 contribute positively and significantly to the supply chain Flexibility.
H5: With an increase in the number of reconfigurability dimensions along the supply chain, more flexibility is achieved in the supply chain.

III. Methodology

The empirical analysis of the research was carried out using the database of the fourth round of the international HPM (High-Performance Manufacturing) project, which was composed of 309 companies from the electronics, machinery, and automotive sectors. The sample comes from 14 countries. Only companies that responded to the form on the Reconfigurability, Flexibility, and Industry 4.0 scales were considered for the research. Each questionnaire was administered to at least two employees from each plant, covering 23 areas within the plant. The questionnaire was validated through reliability and content validity tests by experts. The scales were evaluated perceptually on 1 to 5 and 1 to 7 (1; strongly disagree, 7; strongly agree). The variables assessed were Industry 4.0, analyzed from 4 items; Flexibility, evaluated from 3 items; and Reconfigurability, evaluated from 6 items. The reliability tests resulted in Cronbach's Alpha values greater than 0.85, and each scale's average variance extracted (AVE) was more significant than 0.6. The composite reliability (CR) was more significant than 0.70.

Regarding the model for evaluating the hypotheses for H1 and H2, we use the simple statistical mediation model proposed by Hayes (2018). This method allows the establishment of the direct and direct effects when a mediating variable intervenes along an independent variable, altering the result of the dependent variable (Fig. 1). For H3, H4, H5, the hierarchical regression analysis model was used to evaluate the percentage of explained variance of each dimension of reconfigurability on the flexibility of the supply chain. This method is applied when there are correlations between the independent variables and is appropriate for those sample sets less than 200 (Fig. 2-3). The proposed models are shown below.

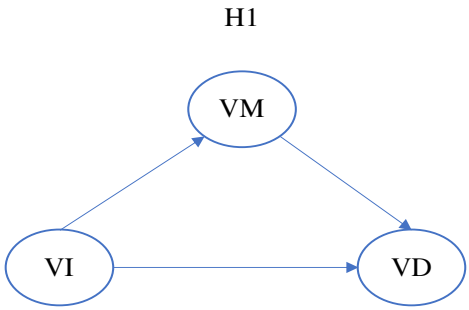

Fig. 1 Statistical mediation model H1.

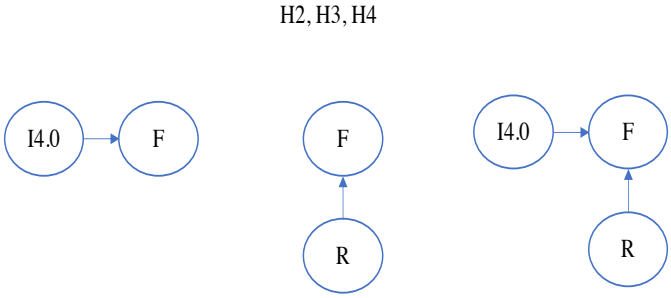

Fig. 2 Hierarchical regression analysis model H2, H3, H4.

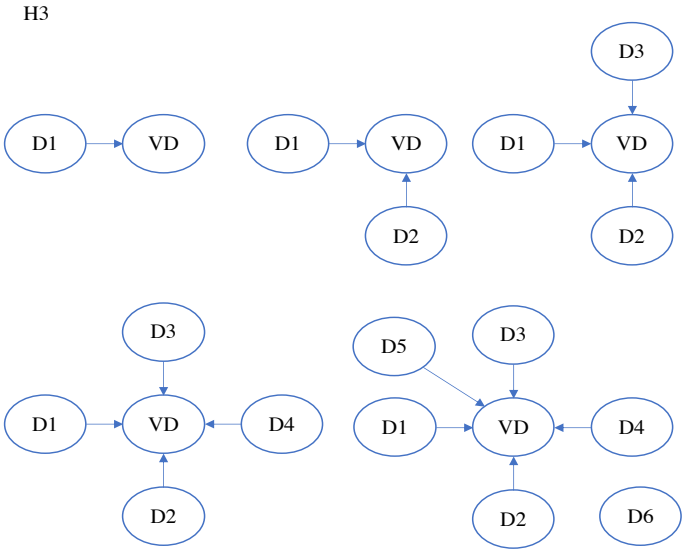

Fig. 3 H5 Hierarchical regression analysis model.

IV. Results

Initially, the study examined reconfigurability, flexibility, and the adoption of Industry 4.0 (I4.0) within the organizations under analysis. The findings reveal a moderate level of reconfigurability across the surveyed companies, scoring an average of 3 on a scale of 1 to 5. Notably, not all companies possess the capacity to adjust their production systems promptly in response to market fluctuations and shifts in demand. In terms of flexibility, the evaluated companies demonstrate a moderately high level, averaging a score of 4 on the 1 to 5 scale.

This suggests a moderate degree of reliability, though challenges persist, such as variability in equipment components and issues with downtime, scrap, and rework in some facilities. The implementation of I4.0 is rated at a medium level, with an average score of 3 on the 1 to 5 scale. This indicates a tepid adoption of I4.0 practices, as not all companies have fully transitioned their production lines. Many are incrementally investing in I4.0 technologies, facing hurdles such as the substantial financial investment required, particularly burdensome for Small and Medium Enterprises (SMEs), and

the challenges associated with recruiting skilled professionals like engineers, data scientists, and software developers.

Sector-wise analysis of reconfigurability reveals varying levels, with the Machinery sector scoring 3.33 and the electronics sector reaching 3.64, while the automobile sector scores 3.30. Flexibility assessment by industry sector showcases the Automobile sector at 3.35, Machinery at 3.33, and Electronics at 3.63, all rated on a scale of 1 to 5.

In terms of I4.0 adoption by sector, the Automobile industry scores 2.99, the Machinery sector 2.96, and the Electronics sector 3.17. The lower adoption rates in certain sectors are attributed to the significant costs, staffing requirements, and operational disruptions associated with reconfiguring production lines, acquiring new equipment, integrating sensors, and implementing software—factors that particularly impact the operational performance of SMEs.

TABLE I
DESCRIPTIVE STATISTICS, RELIABILITY, AND INTERNAL VARIABLE CONSISTENCY

Scala	Mean	Deviation	Cronbach Alpha	AVE	CR
Industry 4.0	3.093	0.824	0.776	0.602	0.873
Reconfigurability	3.497	0.699	0.869	0.755	0.945
Flexibility	3.512	0.713	0.789	0.622	0.879

Following, we meticulously evaluated each hypothesis using the hierarchical regression analysis method. Initially, we scrutinized the correlation between the independent variables to test the hypotheses. The results yielded statistically significant findings ($p < 0.05$), with correlation coefficients ranging from moderate to strongly correlated (all values between 0.30 to 1). This indicates a consistent positive variation among the variables (see Table II). Specifically, modularity and scalability exhibited moderate to strong correlations with each other, suggesting a cohesive relationship. Conversely, diagnosability and personalization demonstrated lower correlation values with modularity and scalability. This implies that within the evaluated plants, only select modules offer the capability for agile and continuous diagnosis and personalization. Furthermore, the requirements for personalization occasionally align with the variants provided by individual modules.

TABLE II
CORRELATION BETWEEN VARIABLES

Reconfigurability	Mod	Scal.	Integ.	Conv.	Diag.	Perso.
Modularity	1					
Scalability	.423**	1				
Integrability	.573**	.431**	1			
Convertibility	.304**	.370**	.448**	1		
Diagnosability	.295**	.346**	.403**	.415**	1	
Personalization	.272**	.296**	.364**	.449**	.453**	1

H1 was evaluated using the simple statistical mediation method, with Industry 4.0 acting as the mediating variable. Supply chain flexibility served as the dependent variable, while supply chain reconfigurability was considered the independent variable. The premise behind this hypothesis is that companies investing in Industry 4.0 tools and methodologies can facilitate faster supply chain reconfiguration and swift responses to market demand. From the mediation analysis presented in Table III, it is evident that there exists partial mediation between the variables under study. Despite a decrease in the level of relationship between the dependent and independent variables, the relationship remains statistically significant. This finding suggests that Industry 4.0 partially mediates the relationship between supply chain reconfigurability and flexibility, aligning with existing literature that underscores the complementary nature of technology and its strategies in enhancing operational efficiency.

While there are alternative avenues for improving organizational flexibility, such as workforce training, supplier/customer collaboration, and continuous innovation, the integration of Industry 4.0 accelerates this process. As more supply chain processes and operations embrace Industry 4.0 dimensions, its mediating role is expected to transition from partial to total mediation. Moreover, in the future, Industry 4.0 may evolve from full mediation to total moderation within the supply chain, given its pivotal role in bolstering operational performance and facilitating rapid responses to market demands. Consequently, H1 is rejected due to the observed partial mediation. Furthermore, the evaluation of H2, H3, and H4 reveals that Industry 4.0 also partially mediated these relationships, as delineated in Table IV.

TABLE III
STATISTICAL MEDIATION RESULTS

Model	***a***	***b***	***c'***	***c***	***Indirect effect***	***Total effect***	***VFA***
R->I->F	0.2992 (p=0.000)	0.1475 (p=0.000)	0.0441 (p=0.00)	0.5762 (p=0.000)	0.0441 (0.0124-0.0855)	0.6203	7.10%
LLCI	0.1406	0.0506	0.0124	0.4621			
ULCI	0.4578	0.2444	0.0855	0.6903			

Table IV illustrates a positive and significant correlation between the variables under consideration. Additionally, upon integrating the two independent variables, there was an enhancement in the indicators (R adjusted increased to 0.397, and the F value surged to 118.01). This improvement signifies an enhancement in the explained variance, corroborating the mediation findings. The partial contribution of mediation results in superior yields or increased supply chain flexibility. Notably, the dependent variable is more accurately predicted when the two independent variables interact synergistically.

Therefore, we accepted H2, H3, and H4. Finally, we evaluated H5 to assess the effect on the supply chain flexibility when companies improve each of the dimensions of the reconfigurability of the supply chain; the results are shown below. Each dimension was considered an individual variable; we included the dimensions individually and were added to the model one by one.

TABLE IV
STATISTICAL MEDIATION RESULTS

	Flexibility		
Correlation	**Model 1**	**Model 2**	**Model 3**
I4.0	0.314		0.623
Reconfigurability		0.608	0.635
F	21.698	65.871	118.011
R2	0.99	0.37	0.397
R2 adjusted	0.94	0.367	0.391
P<0.05	0.000b	0.000b	0.000b

Table V demonstrates that companies emphasizing each dimension of reconfigurability tend to have a more flexible supply chain. As depicted in Table V, the R-value, R-squared, and adjusted R-squared consistently increase as the reconfigurability dimensions are incorporated (models 3 to 6). All models exhibit significance, displaying positive relationships and fitting values. The F value indicates that the tested dimensions significantly contribute to enhancing the flexibility of the supply chain, leading to improved performance.

Moreover, the reconfigurability dimension is attributed to at least 46% of the variability in flexibility. The adjusted R-squared values indicate that flexibility is better elucidated when all components or dimensions of supply chain reconfigurability are involved. Consequently, we accept H5. The flexibility of the supply chain augments with the application of reconfigurability dimensions. Moreover, as a company integrates and refines more dimensions of reconfigurability, it elevates the level of supply chain flexibility. This assertion aligns with the literature reviewed in this research pertaining to supply chain dynamics.

TABLE V
HIERARCHICAL REGRESSION TEST RESULTS (H5)

Flexibility	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
F	70.407	39.405	47.288	37.932	33.637	29.325
R	.509[a]	.532[b]	.645[c]	.659[d]	.679[e]	.688[f]
R square	0.259	0.283	0.416	0.434	0.461	0.473
R square adjusted	0.256	0.275	0.407	0.422	0.447	0.457
Sig. level	.000[b]	.000[c]	.000[d]	.000[e]	.000[f]	.000[g]

V. CONCLUSION AND FUTURE RESEARCH

The fourth industrial revolution, called Industry 4.0, has become transcendental for organizations every day, and has become an effective, efficient, and accelerated channel to adjust to the demands of the markets and the disruptions and turbulence that organizations experience due to globalization. The role that Industry 4.0 plays is that of a mediator, as a complementary but not a substitute tool in the reconfiguration of manufacturing systems. However, in the medium term, it can convert or increase its participation, being a moderator or fundamental factor to rapidly reconfigure operations and, therefore, differentiate and improve the competitive position of companies. Although the implementation cost of Industry 4.0 continues to be a challenge for organizations, its implementation becomes necessary daily.

This research underscores the profound benefits associated with Industry 4.0 technologies and tools, which empower organizations to leverage alternative production schemes, minimize errors, enhance configuration, and expedite production level adjustments. Moreover, Industry 4.0 facilitates seamless information exchange across diverse business facets, including client interactions, material handling, process management, sales, and financial operations. The software and tools derived from Industry 4.0 integrate modules in a practical, agile, and less wasteful manner, featuring dynamic, secure interfaces and improved levels of integration and communication throughout the supply chain.

Integration of Industry 4.0 into reconfigurability accelerates processes, enhances problem detection capacities, augments process control, and reduces failure resolution times, directly impacting quality, costs, and operational performance. Notably, Industry 4.0 plays a pivotal role in bolstering the integration and adaptability of production systems and machinery to meet evolving demands within supply chains. These observations align with existing studies [7,8,9,11,12,13] that emphasize the principles of Industry 4.0 and their direct contributions to enhancing the flexibility of supply chains worldwide. However, it's important to note that this research cannot generalize its results due to its reliance on a specific international project sample, limiting the generalizability of the findings. Further studies across various sectors and companies are warranted to provide additional evidence and validate the theoretical propositions put forth in this research.

Future research that focuses on analyzing the components of Industry 4.0 and its impact on each phase, stage, and dimension of reconfigurability is necessary. Studying or separating the level of application of Industry 4.0 in the supply chain up and down will be required; with this, managers can prioritize all the investments to adjust the supply chain and improve its flexibility by phases, stages, priorities, and spaces of improvement and financial impact as an operation of greater significance. Future research should separately evaluate each dimension to determine its contribution to flexibility and its demands for Industry 4.0 components required to boost companies' supply chains.

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