sustainability

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Assessing Lean 4.0 for Industry 4.0 Readiness Using PLS-SEM towards Sustainable Manufacturing Supply Chain

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Abstract: Lean 4.0 (L4.0) plays a significant role in reducing waste and enhancing productivity for a sustainable manufacturing supply chain in Industry 4.0 (I4.0). L4.0, with its soft and hard practices, may be well integrated into I4.0 to enhance its readiness. Small and medium enterprises (SMEs) are attempting to prepare themselves for I4.0 readiness. Hence, the present research explores L4.0 in terms of its soft and hard practices to understand its holistic relationship with I4.0's readiness for delivering a sustainable manufacturing supply chain. To reap the maximum benefits, several traditional lean thinking practices and lean management principles should be combined with internet-enabled I4.0 technologies. The result of the present empirical analysis revealed that the soft L4.0 practices of top management leadership (TML), customer focus (CF), and employee training and learning (ETL) influence the hard L4.0 practices of total productive maintenance (TPM), statistical process control (SPC), and advanced manufacturing technologies (AMT) to have a positive significant influence on operational readiness (OR) and technological readiness (TR).

Keywords: Industry 4.0; I4.0 readiness; Lean 4.0; PLS-SEM; ANN; soft and hard lean practices

Citation: Qureshi, K.M.; Mewada, B.G.; Kaur, S.; Qureshi, M.R.N.M. Assessing Lean 4.0 for Industry 4.0 Readiness Using PLS-SEM towards Sustainable Manufacturing Supply Chain. *Sustainability* **2023**, *15*, 3950. https://doi.org/10.3390/su15053950

Academic Editor: Mirco Peron

Received: 25 January 2023
Revised: 17 February 2023
Accepted: 19 February 2023
Published: 21 February 2023

1. Introduction

The manufacturing supply chain has experienced a paradigm shift as a result of Industry 4.0 (I4.0) [1]. Firms are integrating new technologies such as the Internet of Things (IoT), cloud computing, data analytics, Lean 4.0 (L4.0), artificial intelligence, machine-to-machine (M2M) communication, and cyber-physical systems (CPS) in their manufacturing activities of production systems. The fourth industrial revolution is based on internet-based technologies. I4.0 enables the implementation of L4.0 to reduce the lead time, labor, material, and equipment resources towards reducing wastage [2,3]. I4.0 includes both major and small and medium-sized firms (SMEs) to significantly contribute to the sustainable growth of the country. Similar to large enterprises, SMEs have also been attempting to transform their activities using L4.0 to become I4.0 oriented. I4.0 is being chosen by businesses seeking improvement in productivity, enhancing economic growth, and ensuring manufacturing sustainability [4]. L4.0 and I4.0 both aim to boost productivity and flexibility in production processes [5]. Lean manufacturing seeks to get rid of all waste in the production process. Several initiatives such as identifying non-productive activities, process streamlining, and standardizing routine formulations may help in waste elimination [6,7].

In the past, lean manufacturing has put a lot of emphasis on being customer-centered. Recently, L4.0 has enabled manufacturing organizations to take a more in-depth look at waste reduction [8]. It is crucial to look at the soft and hard practices of L4.0 as they might have an impact on I4.0. The effect of soft lean practices on hard lean practices and their combined positive effect on business performance has been revealed [9]. L4.0 and green supply chain management play a significant role in I4.0 to offer better opportunities in terms of becoming more efficient and competitive [10]. Lean manufacturing is not redundant with the introduction of I4.0; rather, it helps the firm's lean program become more mature [11]. I4.0 will eventually manifest as parts must be integrated into current lean frameworks, increasing the adaptability of lean manufacturing [12].

A simple soft skill of an employee involving a habit change assists the system in reducing unnecessary delays. Hence, if encouraged and implemented sincerely, it improves the activity's throughput time, thus helping to better realize delivery orders. It has been shown that human factors involving qualitative attitudes and soft skills affect the success of lean implementation [13]. Employee training and learning play a significant role in performance enhancement. Hence, the organization must provide employee training, although the type, extent, and severity of such training may vary depending on the firm's particular needs of I4.0 [14]. It is also concluded that L4.0 soft practices involving people are critical for fostering a long-term continuous improvement environment in an organization [15].

Lean manufacturing helps many firms reduce waste and enhance several performance matrices using statistical process control (SPC). Total productive maintenance (TPM) is a proactive tool in the lean family that aids in providing a competitive advantage and increased performance [16]. Many firms struggle to transform to lean companies [17]. Lean manufacturing and other existing management approaches, such as lean processes, need to change to realize the accomplishment of I4.0, which may be the research need of today. However, there is scarce research on the new opportunities offered by I4.0, which is also termed "smart manufacturing" [18]. As lean implementation works as a complex system of soft and hard lean practices [19], SMEs would benefit from revealing the relationship between these practices. There has not been extensive research carried out on identifying the relationship between soft lean and hard lean and I4.0. Given that L4.0 plays a multifunctional role in I4.0, there has not been much empirical study on it. Based on the aforementioned, the following research questions are posed:

RQ1: What is the relationship between social and technical lean 4.0 practices in accomplishing I4.0 readiness in manufacturing SMEs?

RQ2: What significant relationship do the social and technical lean 4.0 practices have to promote I4.0 readiness?

The paper layout is as follows: In Section 2, we briefly discuss the literature review. Section 3 explains the theoretical framework and hypothesis development of the PLS-SEM and ANN research methodologies. Section 4 presents the methods. Section 5 contains the data analysis and Section 6 provides a discussion of the current study. The research limitations of the present study and future research directions are presented in Section 7. Finally, Section 8 provides the conclusion of this study.

2. Literature Review

I4.0 is impacted by new paradigms in key technologies, which include cloud computing, cyber-physical systems, and the industrial Internet of Things [20]. Furthermore, the main feature of I4.0 is CPS, which leads to an agile and dynamic production system that further depends on knowledge integration and heterogeneous data [21]. I4.0 aims to increase operational productivity and efficiency, while also automating processes to a greater extent [22].

Lean 4.0 (L4.0) was first used in 2017. It combines lean with I4.0 by comparing its compatibility with the technology used in I4.0 with lean. Furthermore, it has been concluded that lean is a prerequisite for digitization [23]. Furthermore, the compatibility of L4.0 with I4.0 was studied and it was found that both complement each other in terms of the lean tools [24]. The effect of organizational culture (OC) and L4.0 soft practices have been tested empirically using a multi-group methodology. It has been revealed that soft LM techniques are used more frequently in successful lean factories than in failing ones [25].

An empirical study of lean practices in SMEs dealing with livestock feed manufacturing organizations concluded that lean soft practices influence organizational readiness in

I4.0 [26]. A study was conducted that illustrated how SMEs can benefit from information technology (IT) usage for L4.0 to sustain competitiveness in I4.0 [27]. L4.0 makes a major contribution to the continuous improvement of I4.0 [28]. The study established that continuous improvement, involving the pull concept along with customer focus, can make the manufacturing supply chain well supported with L4.0. An empirical study involving 200 manufacturing industries was carried out on lean-based production integrating I4.0, leading to lean automation [29]. The study looked into the lean automation association, which combines lean practices and I4.0 technologies to improve operational performance.

I4.0 readiness has been empirically studied in Nepal's industrial sector, and an industrial readiness index for adopting I4.0 has been developed by taking into account various success factors and barriers [30]. Five constructs were used in the conceptual framework and the association with "technology innovation decision making" for I4.0 readiness using SmartPLS was investigated as well as how "government intervention" affects the connection between the constructs and I4.0 readiness. A Malaysian study was carried out to reveal the various factors influencing SMEs' readiness for I4.0 [31]. In their conceptual model, they considered six constructs and investigated their influence on readiness for I4.0 in terms of MR, OR, and TR using SmartPLS. They also looked into the impact of "financial support" on six constructs that influence I4.0 readiness. An empirical study of manufacturing industries was carried out to investigate various relationships of I4.0 drivers using SmartPLS [32]. They also investigated the I4.0 drivers, adopting factors, factors reducing risk, and sustainability factors for organization performance. The I4.0 readiness-based study was conducted to investigate how to implement I4.0 readiness using SmartPLS [33]. Their conceptual model was based on the economic, social, cultural, technological, and environmental dimensions to assess I4.0 readiness.

Manufacturers who have already implemented lean manufacturing need to know how to adapt to the consequences of I4.0 [34]. According to empirical research, 179 industrial firms have already adopted a lean manufacturing approach. Furthermore, they found that while transitioning to I4.0, a lean foundation was deemed essential [35]. Comparable research found that to enhance production performance, lean approaches should embrace advanced manufacturing technologies (AMTs) [36]. According to performance advantages, research categorized lean manufacturing deployments into five categories: (1) financial, (2) operational, (3) human, (4) environmental, and (5) market [37]. The customer-focused smart system helps move towards I4.0 readiness [38]. "I4.0 readiness" is a term used to describe how well-equipped a company is to use digital technologies [39]. Hence, it is important to know the degree of readiness of SMEs to take advantage of I4.0 [30,31,40]. An SME-centric model for I4.0 preparation was developed using empirical research with 110 manufacturing Malaysian SMEs and the unified theory of acceptance and use of technology [31]. I4.0 readiness models were studied for various dimensions [41]. I4.0 readiness models were studied for manufacturing firms [42]. A study leading to the modeling of business for innovation and smart growth in I4.0 for enterprises to become smart and sustainable was carried out [43].

To promote a continuous improvement culture, lean management practices may be adopted. L4.0 is a sophisticated socio-technical system that combines social and technological practices and ought to be continuously used and integrated to promote I4.0 preparedness [15].

3. Theoretical Framework and Hypothesis Development

People and technology together play a significant role in maximizing performance. Both people and technology in isolation can be put to use to enhance maximum performance [44]. The most comprehensive set of conceptual and empirical research behind applications for employee involvement and job design is probably found in the socio-technical system (STS) theory. Furthermore, based on findings from sociological, scientific, and technological studies, as well as evolutionary economics, various strategies have been devised to examine change from the STS perspective [45]. In organizational work design, STS is a method for addressing workplace interactions between humans and technology. STS theory supports the idea that improved performance results from the combined optimization of the technical and social systems of an organization [46]. As per STS theory, industrial competitiveness must be increased through the integration and coordination of strategy, structure, culture, and human resource sub-systems within a complex and dynamic environment [46]. The institutional theory of organization management supports STS theory. Institution theory helps in creating, developing, and implementing institutional setup through organization structure, defined policy, rules, and norms to help organizational activities, its people, and strategies. The spread of operational procedures has been largely explained by institutional theory using the isomorphism principle. Further, it implies that institutional forces cause organizations to grow more similar [47].

The foundation of the lean philosophy is a set of principles that support an organization's process, people, and strategy components. Rather than just deploying a set of technical lean tools, applying the lean concept requires a significant cultural adjustment [48]. Soft lean approaches typically address issues with human resources and behavioral factors. Leadership, education and training, teamwork, customer focus, empowerment, satisfaction, and the use of human resources are a few examples of lean soft techniques. Table 1 describes soft and hard lean practices based on an in-depth review of the literature.

Table 1. Brief description of the soft and hard lean practices.

Type of Lean Practice	Name of the Lean Practices	Description	References
Soft	Continuous improvement	Through incremental and ground-breaking advancements, it is the continuous enhancement of goods, services, or procedures.	[25,49–51]
Soft	Top management leadership	A person's, a group's, or an organization's ability to "lead" other individuals, teams, or entire organizations via influence or direction.	[25,50,52]
Soft	Total employee involvement	It promotes increased involvement of team members, employees, and individual contributors in organizational problem-solving, planning, and decision-making processes.	[50,52]
Soft	Supplier development and partnership	It propagates partnering with long-term external organizations to help internal processes.	[25,50,53]
Soft	Organizational culture	The full collection of attitudes, values, and beliefs that a corporation holds, as well as how they influence how its employees act.	[49–51]
Soft	Training employees	It refers to the ongoing initiatives taken by a business to improve employee performance.	[50,51,54,55]
Soft	Customer focus	It cultivates a workplace culture devoted to raising customer satisfaction and establishing enduring relationships with them.	[56]
Soft	Customer relationship management	It consists of the techniques, strategies, and tools used by organizations in handling and analyzing customers.	[50,53]
Soft	Worker empowerment	The firms' act of giving workers some degree of autonomy and control over their daily tasks.	[57]
Soft	Multi-skilling development	It is the ability to perform multiple tasks at once.	[58]
Soft	Small-group problem solving	It uses the consensus of the stakeholders who participate in decision-making to find the problem's solution.	[50,51,55]

Table 1. *Cont.*

Type of Lean Practice	Name of the Lean Practices	Description	References
Hard	Total quality management	It is a strategic move by the organization to involve everyone from entry-level employees to its highest-ranking executives to focus on quality improvement and ensure customer satisfaction.	[50,53]
Hard	Total productive maintenance	It is a strategic move to involve workers and staff in maintenance-related activities to enhance production.	[50,53]
Hard	Just-in-time delivery by the supplier	It is an inventory management strategy in which suppliers only deliver products as needed.	[50,53]
Hard	Production scheduling and systemization	It is a systematic approach to concerting production plans into a production schedule for flawless production.	[50,55]
Hard	Statistical process control	It involves the use of statistical techniques to track and manage the quality level of the production process.	[25,50,51,55]
Hard	Kanban	It helps track the production and order management of components and materials.	[25,50,55]
Hard	Setup time reduction	An arrangement to speed up the process transition while switching to new manufacturing.	[25,50,55]
Hard	Equipment layout for continuous flow	It is a systematic arrangement for equipment to enable continued product flow.	[50,55]
Hard	Autonomous maintenance	It aims to provide more responsibility to the operator and permits preventive maintenance tasks	[50]
Hard	Lean manufacturing Practices	It is an approach that focuses on reducing waste in production systems while also increasing productivity.	[50,59]

The internal review board was contacted for the required approval following the university policies. Participants completed a permission form after a brief presentation stating their desire to participate in the study and their right to discontinue at any time. It was acceptable for additional responders to decline any questions. It was unanimously decided to for the collected data to be for confidential use, without allowing any direct or indirect benefit from participation. Participants also agreed to the interview being recorded on audio, to remain anonymous, and to the authors' right to preserve the original data. Additionally, access to the information was allowed at any moment and there was complete freedom to get in touch with any participant.

(a) Soft and hard L4.0 practices association and their influence on I4.0 readiness.

Implementing both soft and hard lean methods is part of lean manufacturing. It is further demonstrated that both soft and hard lean techniques are interconnected and have an impact on lean manufacturing [19]. Generally, working managers are convinced and interested in adopting hard lean practices; however, not all convincingly emphasize lean soft practices [60]. Soft practices are crucial for achieving a superior performance in lean manufacturing [50]. According to STS theory, the synchronous alignment of social and technical systems results in a successful system needed for manufacturing supply chain management [61]. Top management leadership plays an important role in adopting L4.0 for I4.0 readiness [62]. Customer-focused activities need a smart system to help with I4.0 [38]. Employee training and learning are crucial for moving towards I4.0 readiness. TPM and SPC help in waste reduction in lean manufacturing systems and help enhance production [63]. Advanced manufacturing technologies such as computer-aided design (CAD) and computer-aided machining (CAM), automated guide vehicles (AGV), robotics, and machine networking help to achieve I4.0 readiness. For every business to transition to I4.0, three distinct dimensions, i.e., "managing", "operational", and "technological", are crucial. Mixed effects, i.e., positive and negative associations on I4.0 readiness are observed to result from organizational capabilities, market pressure, and perceived benefits, as well as a moderating influence from financial assistance for Malaysian SMEs [31]. The Malaysian study also revealed that various variables such as "financial capability", "technical capability", "customer needs", and "perceived benefits" have a positive association with MR, but no association with "perceived opportunities" and "competitive pressure". OR is positively influenced by "financial capability", "perceived benefits", and "customer needs"; however, it is not influenced by "technical capability", "competitive pressure", and "perceived opportunity". Similarly, TR is influenced by "financial capability" and "technical capability", and is not influenced by "perceived benefits", "perceived opportunities", "customer needs", or "competitive pressure".

The I4.0 readiness study carried out in Nepal found that SMEs have a low level of awareness of state-of-the-art technologies leading to I4.0 readiness. Furthermore, the study revealed that SMEs' engagement towards I4.0-related activities is low [30]. Based on the discussed premises and Figure 1, various hypotheses for soft and hard lean practices and their mediating effect have been developed to investigate their association with I4.0 readiness in terms of OR, MR, and TR.

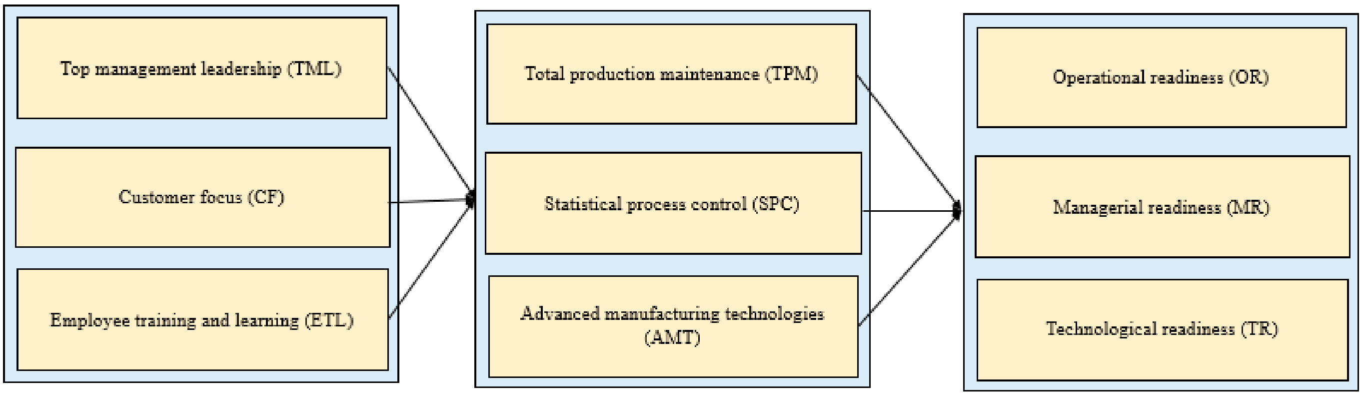

Figure 1. The relationship between soft and hard L4.0 practices, modified from [56,64].

(i) The role of soft L4.0 practices on hard L4.0 practices.

H1: *Top management leadership (TML) has a positive effect over hard L4.0 practices.*

H1a: *TML has an association with total productive maintenance (TPM).*

H1b: *TML has an association with statistical process control (SPC).*

H1c: *TML has an association with advanced manufacturing technology (AMT).*

H2: *Customer focus (CF) has a positive effect on hard L4.0 practices.*

H2a: *CF has a positive association with TPM.*

H2b: *CF has a positive association with SPC.*

H2c: *CF has a positive association with AMT.*

H3: *Employee training and learning (ETL) positively affect hard L4.0 practices.*

H3a: *ETL has a positive association with TPM.*

H3b: *ETL has a positive association with SPC.*

H3c: *ETL has a positive association with AMT.*

(ii) The mediating role of hard L4.0 practices.

H4: *The hard L4.0 (TPM, SPC, and AMT) practices mediate the association between the soft L4.0 (TML, CF, and ETL) practices and I4.0 readiness (OR, MR, and TR).*

H4a: *The hard L4.0 TPM practices mediate the association between the soft L4.0 practices and I4.0 readiness (OR, MR, and TR).*

H4b: *The hard L4.0 SPC practices mediate the association between the soft L4.0 practices and I4.0 readiness (OR, MR, and TR).*

H4c: *The hard L4.0 AMT practices mediate the association between soft L4.0 practices and I4.0 readiness (OR, MR, and TR).*

(iii) Relationship between hard L4.0 practices and I4.0 readiness.

H5a–c: *There is a positive and significant association between TPM I4.0 readiness (OR, MR, and TR).*

H6a–c: *There is a positive and significant association between SPC I4.0 readiness (OR, MR, and TR).*

H7a–c: *There is a positive and significant association between AMT I4.0 readiness (OR, MR, and TR).*

4. Methods

A descriptive-cum-cross-sectional study was carried out. The data from Indian manufacturing SMEs were gathered using an online survey approach with Google Forms. The type of manufacturing SMEs was identified from the size of the enterprise. The investment and turnover of micro-enterprise ranges (<1 crore, <5 crores), the investment and turnover of small enterprise ranges (<10 crores, up to Rs. 50 crores), and the investment and turnover of medium enterprise range (<Rs. 20 crores, Rs. 100 crores). A five-point Likert scale was used, with 1 representing "strongly disagree" and 5 representing "strongly agree".

A database of 420 Indian SMEs involved in manufacturing sectors was prepared from the directory of the Confederation of Indian Industry (CII) using a random selection method. The random selection method helped to provide the required randomness and an equal chance of selection from the SEMs' population in the targeted sample. Generally, manufacturing shop floor managers are considered lean practicing managers. So, for the pilot testing of the questionnaire, a mixed group of academicians and practicing managers were selected. After the pilot survey, three questions were modified based on the responses of the group. Ethical issues in responding to the questionnaire were also taken care of.

The survey was carried out by sending 420 Google Forms links using emails, WhatsApp, Facebook, and LinkedIn. Respondents were also reminded through follow-up reminders. Using the data gathered, 280 survey instruments were collected with a response rate of 66.67%. The data were filtered, thus after the cleaning of the data, the feedback from 220 questionnaires was found to be suitable for further analysis. SPSS 28.0 and SmartPLS 4.0 were used in the data analysis. It has a graphical user interface (GUI) for variance-based SEM that can model latent variables with minimal requirements [65]. Because of the minimal data requirement, simple assumptions, and its ability to model multiple variable relationships, the present study employed PLS-SEM [65]. As it is known, PLS does not demand the data to be normality distributed. Smaller datasets with a nominal, interval, or ratio may be considered for the analysis [65]. Table 2 displays the sample data's demographic statistics.

Table 2. Demographic information.

Variable	Item	Frequency	Percentage (%)
Gender	Male	128	0.582
	Female	92	0.418
Firm size based on employee strength	Micro (1–4)	53	0.241
	Small (5–99)	72	0.327
	Medium (100–499)	95	0.432
Establishment Years	<5	41	0.186
	>5 <10	86	0.391
	>10 years	93	0.423
Industry type	Casting Machining	46	0.209
	Gear manufacturing	30	0.136
	Machines manufacturers	31	0.141
	Surgical parts manufacturers	63	0.286
	Automotive parts manufacturers	19	0.086
	Electrical parts manufacturers	14	0.064
	Other	17	0.077

5. Data Analysis

(i) Descriptive statistics.

This section focuses on the descriptive statistics of the constructs. The detailed descriptive data are shown in Table 3. All of the constructs have a mean above 3.5 and their skewness and kurtosis are within the threshold limit of ±2 [66].

Table 3. Descriptive analysis.

Constructs	N	Mean	Kurtosis	Skewness
Top management leadership (TML)	220	3.5582	0.056	−0.325
Customer focus (CF)	220	3.6805	0.354	−0.040
Employee training and learning (ETL)	220	3.5260	0.377	0.080
Total productive maintenance (TPM)	220	3.8778	−0.168	−0.082
Statistical process control (SPC)	220	3.8812	0.069	−0.342
Advanced manufacturing technologies (AMT)	220	3.8145	0.133	−0.329
Operational readiness (OR)	220	3.8407	0.015	−0.229
Managerial readiness (MR)	220	3.8856	0.085	−0.402
Technological readiness (TR)	220	3.6636	0.328	−0.448

(b) Assessment of measurement model

(i) Reliability and convergent validity measures.

Generally, it is recommended to measure convergent validity and reliability while assessing the model [65]. Additionally, Cronbach's alpha and rho A were employed to illustrate the data's reliability. Item loading and average variance extracted (AVE) are crucial factors to consider in convergent validity. A value for the Cronbach alpha and rho_A greater than or equal to 0.70 was acceptable [65,67]. The AVEs needed to be higher than 0.50 to achieve the convergent outcome [68]. In our analysis, the values of the factor loadings and AVEs for all of the factors were found, as per the recommendations made by Hair et al. [69]. The values were found to be higher than 0.72. As collinearity increased, so too did the estimates of parameter variance [70]. Multicollinearity was used to calculate variance inflation factors (VIF) whose calculated values must be less than 4.0 [69]. In our analysis, the collinearity statistics (outer VIF values) of all of the items had a value of less than four, indicating that the variables had no multicollinearity effect. Table 4 provides information on constructs' reliability and convergent validity.

Table 4. Constructs' reliability and convergent validity.

Constructs	Items	Loadings (>0.70) *	VIF (<5) **	Reliability		Average Variance Extracted (AVE) (≥0.50) **
				Cronbach's Alpha (≥0.70) **	rho_A	
Top management leadership (TML)	TML1	0.723	1.278	0.705	0.715	0.622
	TML2	0.848	3.045			
	TML3	0.813	2.779			
Customer focus (CF)	CF1	0.815	1.766	0.714	0.743	0.633
	CF2	0.833	2.086			
	CF3	0.852	2.223			
	CF4	0.767	1.350			
Employee training and learning (ETL)	ETL1	0.898	2.181	0.848	0.854	0.687
	ETL 2	0.910	2.309			
	ETL 3	0.816	2.487			
	ETL 4	0.789	2.021			
Total productive maintenance (TPM)	TPM1	0.917	2.99	0.761	0.765	0.678
	TPM2	0.796	1.812			
	TPM3	0.944	2.962			
Statistical process control (SPC)	SPC1	0.819	1.808	0.719	0.730	0.642
	SPC2	0.830	1.996			
Advanced manufacturing technologies (AMT)	AMT1	0.914	1.575	0.747	0.748	0.664
	AMT2	0.876	1.570			
	AMT3	0.783	1.845			
Operational readiness (OR)	OR1	0.823	2.370	0.866	0.867	0.713
	OR2	0.782	2.372			
	OR3	0.783	2.243			
	OR4	0.904	1.760			
Managerial readiness (MR)	MR1	0.862	2.560	0.865	0.937	0.695
	MR2	0.885	2.907			
	MR3	0.809	2.096			
	MR4	0.858	2.557			
Technological readiness (TR)	TR1	0.759	1.371	0.779	0.783	0.602
	TR2	0.871	1.764			
	TR3	0.908	2.100			
	TR4	0.728	2.805			

* [69], ** [65].

(a) Discriminant validity

There are several methods that can be used for examining discriminant validity, including the Fornell–Larker criteria, cross-loading, and the HTMT criterion [71,72]. Following Henseler et al. [71], the cross-loading and Fornell–Larker techniques of PLS-SEM cannot identify discriminant validity [73]. As a result, the HTMT method was used to carry out the discriminant validity. For comparable variables, the acceptable value of HTMT was ≤0.90, whereas for different variables, it was ≤0.85 [72]. All of the latent variables' discriminant validity (HTMT) are shown in Table 5, and all constructions complied with the minimum limits of ≤0.85.

Table 5. Discriminant validity.

Latent Construct	TML(1)	CF(2)	ETL(3)	TPM(4)	SPC(5)	AMT(6)	OR(7)	MR(8)	TR(9)
TML(1)									
CF(2)	0.547								
ETL(3)	0.539	0.662							
TPM(4)	0.812	0.597	0.507						
SPC(5)	0.624	0.609	0.475	0.684					
AMT(6)	0.7	0.712	0.536	0.789	0.843				
OR(7)	0.586	0.631	0.459	0.704	0.764	0.829			
MR(8)	0.083	0.076	0.029	0.124	0.058	0.099	0.182		
TR(9)	0.572	0.609	0.434	0.678	0.726	0.821	0.827	0.112	

(b) Assessment of structural model.

In the evaluation of the structural model, it is recommended that the relationship between exogenous and endogenous factors be looked at [72]. The constructed structural model, effect magnitude, and acceptance and rejection of the alternative hypotheses are all detailed in Table 6.

Table 6. Structural model and effect size.

Relation	β	t Value	f^2	CI [2.05%–97.5%]	Decision
H1a: TML→TPM	0.624	29.162	0.062	0.582–0.665	accepted
H1b: TML→SPC	0.34	13.852	0.571	0.292–0.387	accepted
H1c: TML→AMT	0.344	13.858	0.299	0.296–0.393	accepted
H2a: CI→TPM	0.134	5.343	0.126	0.086–0.186	accepted
H2b: CI→SPC	0.295	10.471	0.326	0.24–0.35	accepted
H2c: CI→AMT	0.348	12.639	0.203	0.294–0.401	accepted
H3a: CRM→TPM	0.036	1.675	0.001	−0.077–0.006	accepted
H3b: CRM→SPC	0.083	3.012	0.031	0.03–0.138	accepted
H3c: CRM→AMT	0.088	3.629	0.012	0.041–0.137	accepted
H5a: TPM→OR	0.147	6.71	0.084	0.105–0.19	accepted
H5b: TPM→MR	0.055	1.671	0.049	−0.013–0.112	rejected
H5c: TPM→TR	0.113	5.034	0.042	0.069–0.156	accepted
H6a: SPC→OR	0.212	7.32	0.076	0.153–0.267	accepted

Table 6. *Cont.*

Relation	β	t Value	f^2	CI [2.05%–97.5%]	Decision
H6b: SPC→MR	0.045	0.975	0.192	−0.051–0.132	rejected
H6c: SPC→TR	0.238	7.815	0.032	0.179–0.298	accepted
H7a: AMT→OR	0.466	15.382	0.015	0.408–0.526	accepted
H7b: AMT→MR	−0.003	0.062	0.562	−0.115–0.1	rejected
H7c: AMT→TR	0.425	13.901	0.390	0.366–0.484	accepted

The association between soft L4.0 (TML, CF, and ETL) and hard L4.0 (TPM, SPC, and AMT) was investigated. As per the results of the structural model and effect size, it can be concluded that there was an association between hard L4.0 practices and I4.0 readiness (OR, MR, and TR). The outcomes also show TPM→MR was not found to be positively associated; the same outcomes were attained for other hard practices in L4.0. It was found that the association between SPC→MR and AMT→MR was positively significant, hence, H5b, H6b, and H7b were rejected. As SMEs face liquidity issues in their medium and long-range planning, the managerial commitment towards AMT adoption is less. As AMT involves investment, SMEs defer the induction of AMT and look for government help. Thus, this may indicate that for SMEs, deferring led to the late adoption of Industry 4.0 [74].

(c) Mediation analysis

Table 7 provides the results of various mediation effects resulting from soft L4.0 (TML, CF, and ETL) practices on I4.0 readiness (OR, MR, and TR) through hard L4.0 (TPM, SPC, and AMT) practices. To conduct the mediation analysis in this study, SPSS 28.0 and SmartPLS 4.0 software were used. The findings demonstrate that the relationship between TML→OR and TR, CF→OR, and TR was mediated by hard L4.0 practices (TPM), whereas the relationship between TML→MR, CF→MR, and ETL→OR, MR, and TR was not mediated by TPM. Thus, for TPM, an incomplete mediating effect was found between soft L4.0 practices and I4.0 readiness, and H4a was partially supported. Furthermore, the results highlight that SPC is mediating between TML→OR and TR. Furthermore, SPC demonstrated no mediating effect between CF→I4.0 and ETL to I4.0. It was found that AMT mediated between various soft L4.0 practices and I4.0. The findings indicate a connection between TML→OR and TR, and that AMT positively and significantly mediated OR, TR, and ETL (OR and TR). Thus, H4c was partially accepted. Figure 2 displays the output of SmartPLS.

Table 7. Mediation analysis.

Hypotheses	Relation	B	t Value	*p* Value	CI [2.05%–97.5%]	Decision
H4a:	TML→TPM→OR	0.091	6.591	0	0.065–0.119	accept
	TML→TPM→MR	0.034	1.662	0.097	−0.008–0.071	reject
	TML→TPM→TR	0.070	4.972	0	0.043–0.098	accept
	CF→TPM→OR	0.020	4.023	0	0.011–0.030	accept
	CF→TPM→MR	0.007	1.536	0.125	−0.002–0.017	reject
	CF→TPM→TR	0.015	3.440	0.001	0.008–0.025	accept
	ETL→TPM→OR	−0.005	1.609	0.108	−0.012–0.001	reject
	ETL→TPM→MR	−0.002	1.048	0.295	−0.006–0.001	reject
	ETL→TPM→TR	−0.004	1.577	0.115	−0.009–0.001	reject

Table 7. *Cont.*

Hypotheses	Relation	B	t Value	*p* Value	CI [2.05%–97.5%]	Decision
H4b:	TML→SPC→OR	0.072	6.678	0	0.051–0.093	accept
	TML→SPC→MR	0.015	0.970	0.332	−0.017–0.045	reject
	TMLQ→SPC→TR	0.081	6.868	0	0.059–0.104	accept
	CF→SPC→OR	0.062	5.615	0	0.042–0.085	accept
	CF→SPC→MR	0.013	0.963	0.336	−0.014–0.040	reject
	CF→SPC→TR	0.070	5.874	0	0.048–0.094	accept
	ETL→SPC→OR	0.018	2.806	0.005	0.006–0.031	accept
	ETL→SPC→MR	0.004	0.878	0.380	−0.004–0.013	reject
	ETL→SPC→TR	0.020	2.812	0.005	0.007–0.034	accept
H4c:	TML→AMT→OR	0.160	10.51	0	0.131–0.191	accept
	TML→AMT→MR	−0.001	0.062	0.951	−0.039–0.035	reject
	TML→AMT→TR	0.146	9.775	0	0.117–0.177	accept
	CF→AMT→OR	0.162	9.241	0	0.129–0.198	accept
	CF→AMT→MR	−0.001	0.062	0.951	−0.040–0.035	reject
	CF→AMT→TR	0.148	8.88	0	0.117–0.181	accept
	ETL→AMT→OR	0.041	3.556	0	0.019–0.064	accept
	ETL→AMT→MR	0	0.059	0.953	−0.011–0.009	reject
	ETL→AMT→TR	0.038	3.567	0	0.018–0.059	accept

(d) Artificial neural network (ANN) analysis

The artificial neural network (ANN) has been employed to reveal the variable relationships in the present research. ANNs can identify both linear and nonlinear relationships between decision variables. Neural network models outperform more traditional causal explanatory models such as multiple linear regression, discriminant analysis, and logistic regression [75]. The linear relationship between exogenous and endogenous variables may be explained using SEM and multiple regression analysis (MRA). However, they could fall short in terms of describing the complex nature of the decision-making process [76]. Additionally, it is believed that SEM and MRA are compensatory. It is expected that an increase in other exogenous components within the framework can make up for a loss by increasing other components [56,77]. L4.0 practices are considered non-compensable and essential for I4.0 in the current study. This implies that exogenous constructs have unique conceptualizations and meanings, and a decrease in TML cannot be made up for by an increase in CF and ETL [56].

By design, ANN considers various parameters such input, output, and hidden layers. The feed-forward back propagation algorithm was utilized using a multilayer preceptor following earlier research. The data were divided into two ratios of 90:10, where 90 percent of samples were allocated for training and 10 percent of samples were used for testing, similar to Lim et al. [78]. When using ANN, sensitivity analysis is essential as it allows for the evaluation of each input neuron's predictive ability. ANN was performed using SmartPLS 4.0 and SPSS 28.0 software. Table 8 exhibits the RMSE and sensitivity analysis between input (lean practices) and output neurons (OR). The findings show that ETL had the largest impact on OR with 100% normalized relative importance, followed by SPC (69%), TPM (57%), TML (55%), and AMT (50%). Table 9 exhibits RMSE and sensitivity analysis results for input (lean practices) and output neurons (MR). According to the findings, AMT had a 100% normalized relative relevance and had the greatest impact on MR, followed by SPC (47%), TPM (37%), and CF (33%). Table 10 displays the examination of the RMSE and sensitivity between the input (lean practices) and output neurons (TR). The findings show that AMT, with a 100% normalized relative relevance, had the highest impact on TR, followed by SPC (66%) and CF (47%).

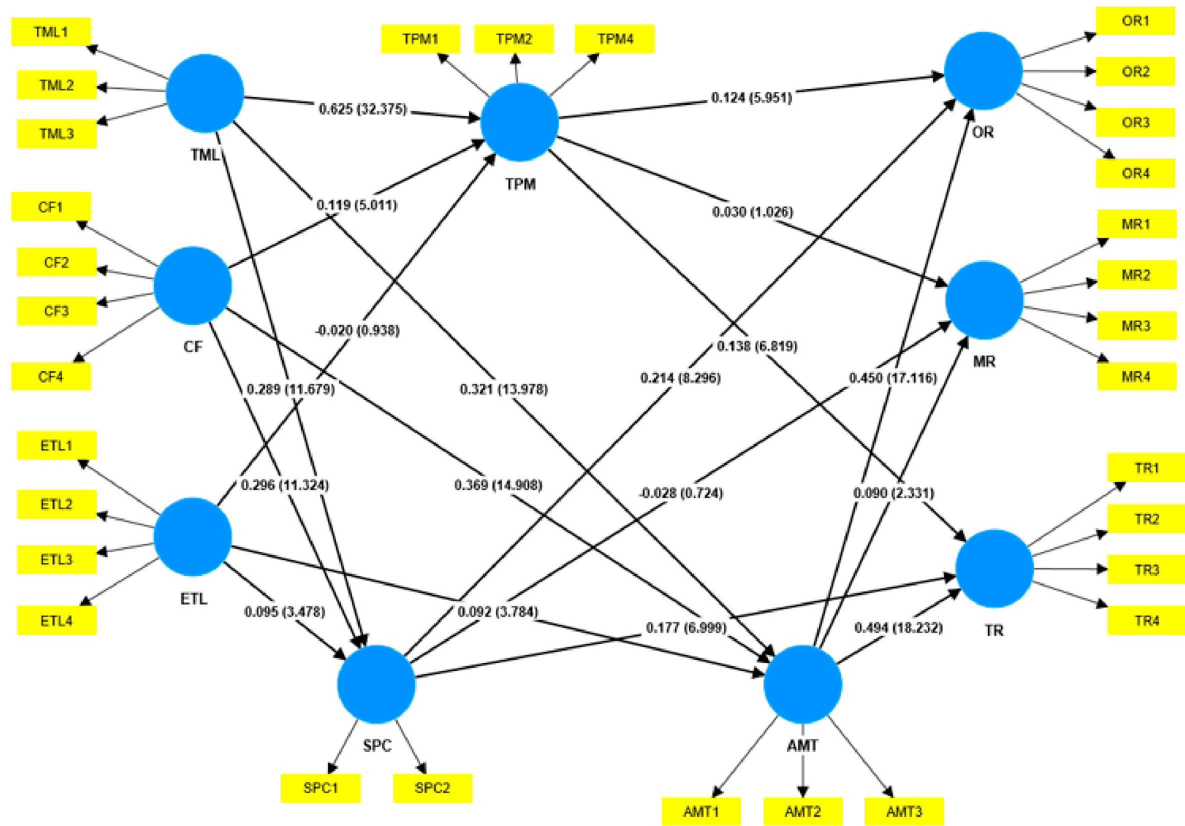

Figure 2. Results of hypothesized model. Legends: Top management leadership (TML), customer focus (CF), employee training and learning (ETL), total productive maintenance (TPM), statistical process control (SPC), advanced manufacturing technologies (AMT), operational readiness (OR), managerial readiness (MR), and technological readiness (TR).

Table 8. RMSE and sensitivity analysis (OR as a dependent variable).

Network	RMSE (Training)	RMSE (Testing)	AMT	CF	TPM	ETL	SPC	TML
1	0.700	0.712	0.324	0.173	0.171	1	0.649	0.384
2	0.705	0.667	0.549	0.42	1	0.816	0.882	0.521
3	0.698	0.649	0.338	0.442	0.821	1	0.969	0.697
4	0.703	0.699	0.448	0.232	0.156	1	0.921	0.093
5	0.696	0.699	0.478	0.508	0.729	1	0.645	0.822
6	0.701	0.764	0.214	0.27	0.329	1	0.396	0.639
7	0.703	0.721	0.214	0.846	0.477	1	0.952	0.427
8	0.705	0.678	0.717	0.141	0.748	1	0.094	0.351
9	0.699	0.732	1	0.26	0.578	0.824	0.395	0.653
10	0.698	0.708	0.496	0.399	0.454	1	0.723	0.699
Mean	0.701	0.703	0.478	0.369	0.546	0.964	0.663	0.529
SD	0.003	0.033						
IMP			50%	38%	57%	100%	69%	55%

Table 9. RMSE and sensitivity analysis (MR as a dependent variable).

Network	RMSE (Training)	RMSE (Testing)	AMT	CF	TPM	ETL	SPC	TML
1	0.497	0.486	1	0.201	0.247	0.147	0.47	0.169
2	0.486	0.475	1	0.313	0.309	0.139	0.43	0.159
3	0.485	0.451	1	0.436	0.392	0.09	0.479	0.168
4	0.480	0.538	1	0.596	0.568	0.453	0.667	0.364
5	0.496	0.449	1	0.268	0.462	0.12	0.644	0.278
6	0.492	0.446	1	0.221	0.215	0.133	0.27	0.224
7	0.482	0.461	1	0.292	0.284	0.032	0.407	0.084
8	0.500	0.494	1	0.292	0.213	0.032	0.364	0.167
9	0.483	0.491	1	0.428	0.456	0.142	0.602	0.255
10	0.493	0.443	1	0.295	0.52	0.165	0.513	0.281
Mean	0.489	0.473	1	0.3342	0.3666	0.1453	0.4846	0.2149
SD	0.007	0.030						
IMP			100%	33%	37%	15%	48%	21%

Table 10. RMSE and sensitivity analysis (TR as a dependent variable).

Network	RMSE (Training)	RMSE (Testing)	AMT	CF	TPM	ETL	SPC	TML
1	0.520	0.485	1	0.262	0.107	0.09	0.692	0.316
2	0.513	0.497	1	0.356	0.122	0.132	0.407	0.098
3	0.507	0.458	1	0.328	0.224	0.101	0.371	0.141
4	0.507	0.498	1	0.524	0.354	0.211	0.558	0.276
5	0.517	0.541	1	0.628	0.399	0.319	0.779	0.246
6	0.524	0.506	1	0.616	0.113	0.069	0.743	0.296
7	0.510	0.497	1	0.354	0.245	0.155	0.508	0.099
8	0.511	0.476	1	0.362	0.28	0.165	0.738	0.203
9	0.537	0.531	0.599	0.699	0.665	0.35	1	0.318
10	0.515	0.511	1	0.421	0.3	0.135	0.57	0.195
Mean	0.516	0.500	0.960	0.455	0.281	0.173	0.637	0.219
SD	0.009	0.025						
IMP			100%	47%	29%	18%	66%	23%

6. Discussion

The primary objective of the present research was to reveal the influence of soft and hard lean practices of lean manufacturing on I4.0 readiness in terms of operational, managerial, and technological accomplishments. In the second step, the influence of both soft and hard L4.0 and I4.0 readiness was assessed. After accomplishing the first research question, seven hypotheses were formulated and empirically examined using PLS-SEM. Later, the ANN technique was employed to accomplish the second research question.

The present research was conducted to investigate the relationship between social and technical L4.0 practices in accomplishing I4.0 readiness in the manufacturing supply chain of SMEs. The influence of soft and hard lean practices on I4.0 readiness was studied and revealed the positive influence over it. The soft and hard L4.0 practices may influence I4.0 directly and indirectly, hence they were tested. TPM, SPC, and AMT hard practices play a mediating role in accomplishing I4.0 readiness, hence it was further studied. At the end of the empirical analysis, it was revealed that there was a positive association between soft and hard lean practices. The results revealed that they were consistent with those from the past [15]. The initial improvements in operational performance were found to have been accomplished because of lean practices. However, to avoid the loss of these initial gains, the organization should continue to practice L4.0 soft and hard practices. The soft and hard L4.0 practices will help organizations achieve sustainable results over the long term by accomplishing I4.0.

Employee training and learning is essential for moving towards I4.0 readiness. Employee training will help enhance employee skills to accept new technologies in manufacturing. The specialized digital and advanced training will further restrict their employees from reverting to their traditional ways of accomplishing the task. SMEs using TPM and SPC will be able to reduce waste minimization owing to the manufacturing process, machines, and equipment. AMT involving CAD, CAM, AGV, and robots is helping to build a CPS, which is the basic need of I4.0 [79].

In a previous study, the involvement of managers not embarking on lean practice implementation was studied. The first major cause was revealed to be the poor implementation of inadequate knowledge. The second cause was apathy toward acquiring new knowledge, so lean implementation is directly related to the knowledge of lean possessed by the managers in charge of designing and implementing it into the system [13].

The secondary objective was to reveal the association of social and technical lean 4.0 practices to accomplish I4.0 readiness in SMEs. ANN was employed for accomplishing this research question. The analysis revealed that soft lean practices such as "top management leadership", "customer focus", and "employee training and learning" play a vital role in accomplishing I4.0 readiness in manufacturing SMEs.

The study involving the association between lean practices (both soft and hard) and the physical work environment and job characteristics directly influences operational productivity in the short term. In the long term, operational performance is influenced by employee behavior, work environment, and the type of job [80]. An empirical study involving soft lean practices confirmed that they enhance organizational lean readiness for successful L4.0 in I4.0 [26]. I4.0 readiness may vary from sector to sector among the operational, managerial, and technological domains. In operational readiness, it takes time to acquire operational resources, prepare infrastructure, develop teamwork among staff, and equip them with the necessary technical skills. To prepare for I4.0, obvious recommendations to SMEs could be to engage in more and more technical skill development programs to upskill their current employees and acquire more technologically adept employees. Governmental organizations or confederations of industries should lead from the front to provide a more theoretical and practical base to induct new knowledge, leading to I4.0 readiness.

7. Research Limitations and Future Research Directions

The present study was undertaken to investigate the soft and hard L4.0 practices toward I4.0 readiness to gauge operational readiness, managerial readiness, and technical readiness. Given the abundance of soft and hard L4 practices, only three soft and hard lean practices were considered for assessing I4.0 readiness; thus, the results are based on a small number of lean practices. Thus, the present study is limited to gauging I4.0 readiness; hence, future studies may imbibe more variables belonging to soft and hard lean practices that influence I4.0 readiness in SMEs. The comprehensive inclusion of various technologies will improve the present findings and guide SMEs toward I4.0 readiness in terms of OR, MR, and TR.

The present study was focused on the manufacturing sector of SMEs; hence, future research might be considered in other sectors covered by SMEs. A future study could look into the relationship between critical success factors (CSFs) and barriers and how they relate to I4.0 readiness. In the future, studies may be conducted to investigate the association between employee awareness, management willingness, product or service selection, available technologies, culture, and financial capability in adopting L4.0 toward I4.0 readiness. A more parameter-based empirical investigation in the service industries may be planned for future study.

8. Conclusions

I4.0 opens the door to new technology, ushering in a paradigm shift in manufacturing development. These avenues are also associated with several challenges that must be overcome to accomplish I4.0 readiness in terms of OR, MR, and TR. The present research investigates L4.0 soft and hard practices to investigate I4.0 readiness. The present empirical study reveals that there a gap in the managerial readiness of SMEs to be I4.0 ready still exists. Indian manufacturing SMEs are embarking on the L4.0 to achieve I4.0 readiness and be on par with global SMEs. SMEs need to gear up in various areas to be leaders in I4.0 readiness. In terms of soft and hard practices, L4.0 has good potential to help with I4.0 readiness.

The present research provides various inputs to explore lean manufacturing in the context of I4.0 readiness. The influence of soft and hard lean practices over I4.0 readiness is investigated for the manufacturing sector, which will be useful for SMEs. L4.0 in its digitized form will help I4.0 readiness by adopting various soft and lean practices. It has been seen that lean practices have a positive association with hard–lean practices. Furthermore, soft–lean practices depend largely on top management and employees' knowledge, willingness, understanding, and practices. The availability of infrastructure influences lean-based practices. When hard lean practices such as TQM, SPC, and AMT are supported by top management through their leadership, commitment, and strategic policy for employee training and customer-focused activities, they have a big effect on OR, MR, and TR. The SME sector struggles with the availability of financial support for imbibe state-of-the-art technologies to have a cutting edge to surpass the pressure of world-class competitiveness and be on par with I4.0 readiness.

Author Contributions: Conceptualization, K.M.Q., B.G.M., S.K. and M.R.N.M.Q.; methodology, K.M.Q., B.G.M., S.K. and M.R.N.M.Q.; software, S.K. and M.R.N.M.Q.; validation, K.M.Q., B.G.M., S.K. and M.R.N.M.Q.; formal analysis, K.M.Q., B.G.M., and S.K.; writing—original draft preparation, K.M.Q., B.G.M. and S.K.; writing—review and editing, K.M.Q., S.K. and M.R.N.M.Q.; supervision, S.K. and M.R.N.M.Q.; project administration, S.K. and M.R.N.M.Q.; funding acquisition, M.R.N.M.Q. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Deanship of Scientific Research, King Khalid University, Kingdom of Saudi Arabia, and the grant number is RGP.1/373/43.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: We would like to express our gratitude to the Deanship of Scientific Research, King Khalid University, Kingdom of Saudi Arabia, for funding this work, as well as to family, friends, and colleagues for their constant inspiration and encouragement. The infrastructure support provided by Parul University, Vadodara, and FORE School of Management, New Delhi, is greatly appreciated.

Conflicts of Interest: The authors declare no conflict of interest.

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