Assessing Lean 4.0 critical success factors (CSFs) for implementing in small and medium-sized enterprises (SMEs)

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Abstract

Purpose – The present research identifies and prioritizes the critical success factors (CSFs) for Lean 4.0 (L4.0) implementation in small and medium enterprises (SMEs). L4.0 integrates Lean principles with Industry 4.0 (I4.0) technologies, for instance wireless networks, Internet of things (IoT), big data, cloud computing (CC), etc., offering significant opportunities to enhance operational efficiency by reducing non-value-adding activities.

Design/methodology/approach – This research adopts the "Fuzzy Decision-Making Trial and Evaluation Laboratory (FDEMATEL)" methodology to examine and assess the connections between CSFs for L4.0 implementation. Data were gathered from SMEs using qualitative and quantitative approaches to ensure comprehensive insights into the critical enablers of L4.0 adoption.

Findings – The study identifies Top Management Support and Commitment, Employee Training and Financial Capabilities as the most important CSFs for L4.0 adoption in SMEs. These factors significantly impact the adoption process, providing actionable insights for SME leaders to overcome challenges and optimize implementation strategies.

Originality/value – This study contributes to the growing knowledge of L4.0 by highlighting key CSFs relevant to SMEs, a sector often constrained by resources but crucial for economic development. The findings provide a practical roadmap for SME entrepreneurs to achieve operational excellence and competitiveness through effective L4.0 adoption.

Keywords Critical success factors (CSFs), Fuzzy decision-making trial and evaluation laboratory (FDEMATEL), Industry 4.0 (I4.0), Lean 4.0 (L4.0), Small and medium enterprise (SME)

Paper type Research paper

1. Introduction

Lean is a management concept that helps firms stay competitive by eliminating waste from processes. Lean 4.0 (L4.0) emphasizes value-adding and continuous improvement as strategies to reduce waste in manufacturing processes. Industry 4.0 (I4.0) has a foundation of modern technologies, whereas L4.0 is a combination of processes and mankind. I4.0 Wi-Fi-based technologies combined with the L4.0 manufacturing principles assist companies in attaining higher productivity. The combination of modern Wi-Fi-based technologies with lean principles helps companies to increase their efficiency. L4.0 technology provides a clear picture of the inventory list and assists in applying just in time (JIT). L4.0 uses I4.0 Wi-Fi-based technologies to discover the machine's accuracy status. Removing non-value-added

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activities from the manufacturing process helps the organizations to reduce the production time. Lean manufacturing is based on customer focus and can manage waste reduction using L4.0 technologies. Several Wi-Fi-enabled technologies can be implemented in various I4.0, for instance, additive manufacturing (AM), automated guided vehicles (AGV) and big data analytics (BDA) that contribute towards waste minimization in production processes (Javaid *et al.*, 2022). L4.0 can be accomplished using several Wi-Fi-enabled technologies like the Internet of things (IoT), big data, real-time data, cloud computing (CC), robots and predictive analytics. Production management has adopted lean methodologies into its day-to-day activities. L4.0 blends I4.0-related technologies with production or lean manufacturing concepts and practices. L4.0 reduces waste and complexity by addressing the waste reduction and complementarity between lean and I4.0. The digital technology supports L4.0 well to fit in the I4.0 (Cifone *et al.*, 2021). Lean helps in waste reduction in manufacturing processes (Fercoq *et al.*, 2016).

Since the I4.0-related technologies enhance industrial performance (Dalenogare *et al.*, 2018), L4.0 may also help. The rise in production cost, market competition, and product pricing poses several challenges to SMEs, hence SMEs must adopt an L4.0 to get rid of all the unnecessary costs. Since SMEs contribute significantly to the nation's long-term growth, they are the backbone of many national economies and help the nation to grow in terms of productivity and employability. Top Management plays a major role in transforming the SME organization into a productive digital transformation using digital technologies for L4.0 implementation. SMEs can expand their process capabilities to improve their production by using digital technologies such as big data, artificial intelligence (AI), 3D printing, cyber security, virtualization, etc. Many SMEs are implementing the lean production system and want to move towards L4.0. The Wi-Fi-enabled technologies in I4.0 are the path-breaking and motivating factor in implementing L4.0 in manufacturing processes. The manufacturing organization may be divided into two major groups, i.e. large enterprises and SMEs. The former have sufficient infrastructure and different technology-based manufacturing setups for smooth and fast production to compete with the local and global markets. However, SMEs struggle a bit because of constraints in technological setup, infrastructure shortages, insufficiently trained staff, and financial shortages for introducing new manufacturing approaches. SMEs are considering implementing a lean transformation; however, they are in a dilemma of implementing it. SMEs struggle in several areas of the L4.0 implementation program.

To withstand the current global business pressures, Indian SMEs must implement lean-based man-factoring strategies. The lean manufacturing method aids in reacting to local and global demand while also ensuring long-term manufacturing sustainability. L4.0 also helps boost manufacturing sustainability (Qureshi *et al.*, 2022). L4.0 improves organizational competitiveness, which strengthens its readiness for I4.0. To prepare for I4.0, SMEs' Top Management can plan their investments in technology, infrastructure, and employee training. The L4.0. Implementation is possible in several manufacturing setups by applying lean tools, carrying out the plant layout analysis, examining the process flow, and investigating the batch size to improve the overall equipment effectiveness (OEE). It has been seen that improper implementation lean method leads to several issues for SMEs. The problem may lead to the ineffective use of infrastructure like men, machines, materials, methods, and matrices. The employee may lose confidence in the process. Several authors came up with several factors known as CSFs for the effective implementation of L4.0 (Ojha, 2022; Khin and Hung Kee, 2022; Ciano *et al.*, 2021).

L4.0 can be implemented in various sectors of SMEs by examining the current companies' scenarios. Before implementing L4.0 in SMEs, a readiness study may be conducted by identifying challenges that may oppose L4.0 implementation. L4.0 CSFs could aid SMEs in successfully implementing L4.0. Therefore, the present study contributes to successful L4.0 implementation.

It is essential to identify and analyze L4.0 CSFs by adopting digital technologies in SMEs for successful implementation. Thus, under the realm of I4.0, SMEs must identify the L4.0 CSFs for implementation.

The present research helps entrepreneurs identify the critical success factors (CSFs) in the SMEs for L4.0 implementation. The following are the research questions (RQs):

RQ1. To identify the CSFs that help L4.0 implementations in the context of SMEs.

RQ2. How these CSFs influence each other in the L4.0 adoption process leading to sustainability practices for SMEs?

The paper has been structured in to six sections: The next section provides the literature review. The research approach is examined in Section 3. Section 4 discusses the data analysis and findings. Study implications are documented in Section 5. Section 6 provides the results, limitations, and future research direction on L4.0 CSFs.

2. Literature review

Lean practices are regarded as management's first choice for improving organizational performance and, ultimately, achieving sustainability. As a result, SMEs are operating according to lean principles (Yadav *et al.*, 2021). Additionally, to tackle the new problems in production processes, SMEs need to adopt lean and environmentally friendly procedures in product and operation management (Oliveira *et al.*, 2018). Research on L4.0 applicable to I4.0 to enhance production excellence was carried out by considering 18 CSFs for big data in manufacturing (Ojha, 2022). Employee motivation plays a big role in a new technology acceptance; hence, employees must be guided towards the integration of new technologies in L4.0. Integrated methodologies of "Fuzzy DEMATEL" and "Fuzzy Delphi" were employed to determine the significant factors for I4.0 to attain overall excellence (Samanta *et al.*, 2024). L4.0 can be achieved with the use of various I4.0-related technologies. The study provided highly significant fourteen I4.0 applications for the manufacturing industries (Javaid *et al.*, 2022). A study on lean tool conversion using digitalization emphasizes that nearly 27 lean-based approaches are in line with I4.0 technologies that can be implemented using AM, AGV and BDA (Valamede and Akkari, 2022). L4.0 and I4.0 can offer several benefits based on various Wi-Fi-enabled technologies to encourage waste minimization in production processes. A study based on structural equation modelling (SEM) was carried out to emphasize the role of L4.0 in enhancing financial performance through waste reduction in the manufacturing process (Qureshi *et al.*, 2023a; Yadav *et al.*, 2024a). To determine the determinants influencing SMEs' adoption of digital technology, an empirical study comprising 15,346 SMEs from the European Union and non-EU was carried out. The result revealed that technology plays an important role in digital technology adoption in transforming employee skills in the adoption of L4.0 (Omrani *et al.*, 2022).

A case study from Turkey shows that various factors such as automation, cyber security, 3D printing, sensor technologies, virtualization, advanced robotics systems, etc. affect digital transformation in the manufacturing sector. SMEs can use various software programs to obtain benefits from information and communications technology (ICT) (Ulas, 2019).

Nozari and Aliahmadi (2022) examined internal linkages of L4.0 CSFs modeled using a nonlinear fuzzy-based methodology. They also examined the influence of lean CSFs using SEM (Noori, 2015). The study revealed that CSF has a moderating effect and offers helpful assistance in establishing connections between lean outcomes and implementation elements. Qureshi *et al.* (2023b) and Yadav *et al.* (2024b) employed "PLS-SEM" to analyze the "CSFs of L4.0" implementation in I4.0 for sustainable manufacturing supply chains.

A multi-case study approach (Bhattacharya and Ramachandran, 2021) was used to implement L4.0 in SMEs. The study recommended upscale lean manufacturing practices across the micro, small and medium enterprises (MSME) sector to realize the lean benefits and invest in sustainable I4.0 so that advanced digital production techniques persist in MSMEs. An empirical study imbibing quality and quantitative factors was taken into consideration for MSMEs by going through online and personal surveys (Bahulikar *et al.*, 2023). The study reveals that lean thinking principles and techniques in accomplishing I4.0 are helpful. The author also provided a theoretical framework based on lean integration with I4.0. The provided framework can also be implemented in MSMEs. A case study dealing with challenges and opportunities for L4.0 implementation in Indian SMEs was carried out (Kumar and Kumar, 2024). The study emphasized resolving the difficulties faced by Jharkhand's SMEs. An evaluation study of CSFs for the successful implementation of Lean Six Sigma in Indian SMEs (Sumant *et al.*, 2024). The study further revealed that efficiency and quality through Lean Six Sigma can provide invaluable insights into the Indian SME sector by informing decisions of their CEO, policymakers and stakeholders. Table 1 depicts the list of L4.0 CSFs along with their description and references.

Table 1. List of Lean 4.0 CSFs along with its description and references

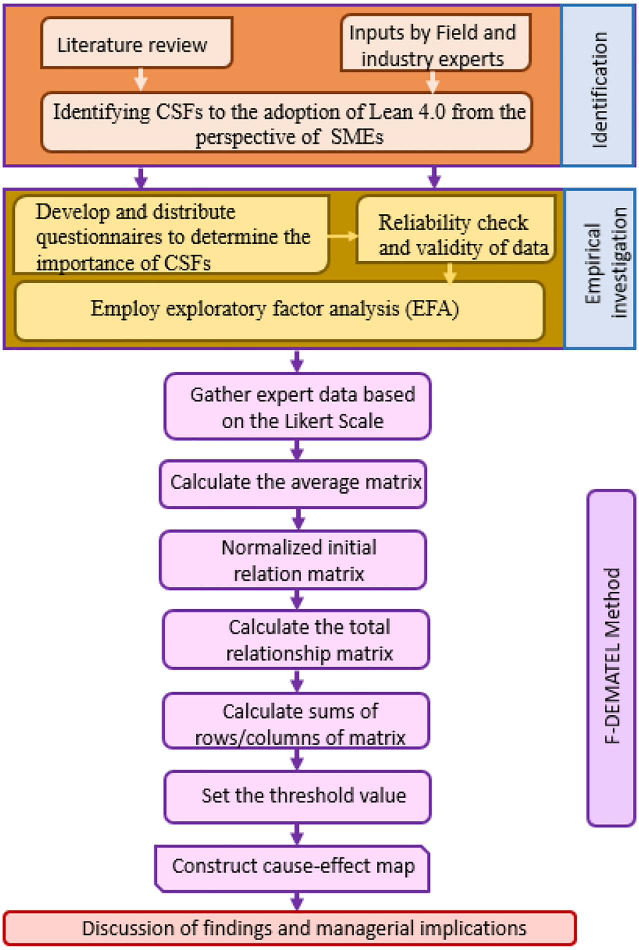
Sr.No.	CSFs	Description	References
C1	Top management support	It plays a vital role in the success and sustainable growth of the SMEs. It helps in strategic decision-making to achieve the goals	Ojha (2022), Qureshi *et al.* (2022)
C2	Wifi-enabled technologies	Technologies such as IoT, CC and augmented reality help in realizing L4.0 in I4.0	Qureshi *et al.* (2022)
C3	Employee training	Employee training helps the employee to enhance work-enabled technology	Stanica and Peydro (2016), Saniuk *et al.* (2021), Ojha (2022)
C4	Employee readiness for change	The employee's resistance to change opposes the employee's readiness to assist in I4.0	Khin and Hung Kee (2022)
C5	L4.0 awareness	The attempt of management and employees to make themselves aware of L4.0-related requirements to realize I4.0	Ciano *et al.* (2021), Qureshi *et al.* (2022)
C6	Prioritizing the lean tools and practices	It helps SMEs to adopt lean tools and practices that improve quality, reduce cost while minimizing waste, and achieve customer satisfaction by reducing delivery time	Khin and Hung Kee (2022), Qureshi *et al.* (2022)
C7	Long-term vision	Long-term vision plays a key role in setting long-term goals to adopt L4.0 in I4.0 and motivate employees to achieve them. It is essential for SMEs to survive the competitive business market	D'Orazio *et al.* (2020), Qureshi *et al.* (2022)
C8	Security of data and foolproof cyber security	It plays a critical role in safeguarding and protecting SMEs against cyber threats and protecting customer information. It also reduces financial losses and is necessary in this digital era	Tjahjono *et al.* (2017), Ciano *et al.* (2021)
C9	I4.0 strategy implementations	An effort to consistently develop and put into action plans for the I4.0	Cañas *et al.* (2021), Qureshi *et al.* (2022)
C10	Funds/resource availability	It contributes to the ongoing maintenance of infrastructure resources to meet the I4.0 criterion	D'Orazio *et al.* (2020), Qureshi *et al.* (2022)
C11	Machine-to-machine communication (M2M)	Through a communications channel, it enables direct machine-to-machine (wireless or wired) communication	Tjahjono *et al.* (2017), Ciano *et al.* (2021)

Source(s): Authors' own work

3. Research methodology

The methods used in this study are illustrated in Figure 1. The research builds a theoretical foundation for the problem integrating qualitative and quantitative approaches using empirical analysis. The empirical investigation of CSFs insights from the direct and indirect experiences of respondents. This study focuses on identifying and evaluating the CSFs for adopting L4.0 in SMEs. The CSFs identified in the literature were validated based on respondents' perceptions of their relevance and applicability. To achieve this, data were collected from various manufacturing sectors within the SMEs using both online and offline methods.

This empirical approach validates the CSFs, supporting the practical implementation of L4.0. The study further determines the cause-effect relationships among CSFs. The data have been verified for their reliability and successive validity using "Cronbach's alpha (α)," while "Exploratory Factor Analysis (EFA)" was used to classify the CSFs. Bias checks were also conducted to ensure data integrity.



Source(s): Figure by authors

Figure 1. Research methodology

3.1 Fuzzy DEMATEL method

FDEMATEL a "multi-criteria decision-making (MCDM)" method helps in revealing and assessing the causal relationship between various criteria that pose the complexity challenge (Yadav *et al.*, 2024a, b). The comprehensive technique shows how the requirements directly relate to one another criteria. It also helps to reveal how far the criteria interact. The FDEMTEL is an ideal approach to revealing the overall influence strength for all criteria. It also helps in knowing the criteria of causal relationships either direct or indirect if exist. It helps in measuring the criteria interdependencies under study are measured efficiently.

The FDEMATEL involves the following steps:

Step 1: Data collection along with relevant information:

This step involves the decision-makers (DMs) and the relevant committee for their feedback. The DM committees, which comprise professionals from academia and industries, must be consulted for pertinent information.

Step 2: Formulation of criteria and survey

Formulation and transfer of the evaluation criteria for the survey are crucial. If there are disagreements over the criteria selection process, the DM panel must repeat their discussion of the previously relevant information until they reach a point of agreement.

Step 3: Collection of responses from DMs

In this step, the responses were collected from the DMs in crisp numbers and then converted into Triangular fuzzy number (TFN) numbers.

Step 4: Converting TFNs to crisp value

Based on input from the DM, it is essential to initially transform the linguistic scale into a TFN. These fuzzy numbers must then be converted back to a crisp value using the fuzzy assessments. The detailed procedure is explained in equations from (1) to (9). The "T" denotes the initial direct relationship matrix that can be prepared by aggregating the crisp information gathered from the DM committee.

Step 5: Use of causal effect diagram for criteria analysis

The aggregated crisp value constitutes the matrix T known as the "initial direct relation ". It imbibes pair-wise comparisons to form "$n * n$". The T_{ij} denotes how far the criterion i influences criterion j.

$$\mathrm{T} = \left[T_{ij}\right]_{\mathrm{n*n}}$$

Let us consider that there is a k expert in the DM committee that considers the fuzzy weight $kW_{ij} = (kW_{1ij}, kW_{2ij}, kW_{3ij})$ of the challenges associated with the adoption of L4.0, then the normalization can be obtained using Equations (1–7):

$$x\alpha_{1ij}^{k} = \left(\alpha_{1ij}^{k} - \min \alpha_{1ij}^{k}\right) \Big/ \Delta_{min}^{max}$$

$$x\alpha_{2ij}^{k} = \left(\alpha_{2ij}^{k} - \min \alpha_{2ij}^{k}\right) \Big/ \Delta_{min}^{max} \quad (1)$$

$$x\alpha_{3ij}^{k} = \left(\alpha_{3ij}^{k} - \min \alpha_{3ij}^{k}\right) \Big/ \Delta_{min}^{max}$$

Calculation of left (l_s) and right (r_s) normalization value

$$xls_{ij}^{k} = x\alpha_{2ij}^{k} \Big/ \left(1 + x\alpha_{2ij}^{k} - x\alpha_{1ij}^{k}\right) \tag{2}$$

$$xrs_{ij}^{k} = x\alpha_{3ij}^{k} \Big/ \left(1 + x\alpha_{3ij}^{k} - x\alpha_{2ij}^{k}\right)$$

Calculation of crisp value

$$x_{ij}^{k} = \left[xls_{ij}^{k}\left(1 - xls_{ij}^{k}\right) - \left(xrs_{ij}^{k}\right)\wedge^{2}\right] / \left(1 - xls_{ij}^{k} + xrs_{ij}^{k}\right) \tag{3}$$

Calculation of total normalized crisp value

$$w_{ij}^{k} = \min \alpha_{ij}^{n} + x_{ij}^{n} \Delta_{min}^{max} \tag{4}$$

The average value may be established using the feedback of k DMs.

$$w_{ij}^{k} = \frac{1}{K}\left(w_{ij}^{1} + w_{ij}^{2} + \ldots + w_{ij}^{k}\right) \tag{5}$$

A matrix using the aggregated feedback form k DMs can be generated.

Further, using Equation (6), the matrix "D" may be generated.

$$D = k \times T \tag{6}$$

$$k = \frac{1}{\max\limits_{1 \le i \le n} \sum_{j=1}^{n} x_{ij}}, i, j = 1, 2, \ldots, n \tag{7}$$

Based on the normalized direct relation matrix "D," matrix "M" a total relation matrix may be derived, using Equation (8).

$$\mathrm{M} = D\,(I - D)^{-1}$$

After obtaining the matrix M, the next step is to develop a causal diagram. The sum of the row (*Ci*) and some of the columns (*Ri*) is calculated in the total relation matrix. A causal relationship can be constructed using $(C_i + R_i)$ and $(C_i - R_i)$. The "Prominence" is obtained by $(C_i + R_i)$; it shows the total importance of the challenges on the horizontal axis. $(C_i - R_i)$ is depicted on a vertical axis known as "Relation" can be obtained. If the $(C_i - R_i)$ is positive, the challenges or criteria belong to the cause group; otherwise, it is in effect group if $(C_i - R_i)$, is negative. A cause-and-effect relationship matrix is derived using Equations (8) and (9) using "M."

$$C_i = \left[\sum_{i=1}^{n} T_{ij}\right](1 \times n) = \left[T_j\right](n \times 1) \tag{8}$$

$$R_i = \left[\sum_{j=1}^{n} T_{ij}\right](1 \times n) = \left[T_j\right](n \times 1) \tag{9}$$

4. Data analysis and findings

4.1 Data collection

An empirical survey was carried out to identify and prioritize the CSFs for L4.0 implementations in SMEs by sending 420 questionnaires using social media. Personal interviews were also carried out to ascertain a good response rate. A total of 280 survey instruments were returned giving a response rate of 66.67%. On filtering, the responses 200 feedback were found to be for subsequent EFA analysis using SPSS 28.0. Table 2 depicts the demographic profile of the respondents.

4.2 Data analysis and checking for reliability and validity

The collected feedback was analyzed to find the mean and standard deviations (SD). All the CSFs of L4.0 were found to have a mean value of above 3.45. EFA was conducted to reveal the component matrix. The EFA approach is generally applied to determine the structure of factors. EFA is preferred over other approaches because of several benefits where the loss of minimum information can reduce the list of many variables into a smaller structure. “Bartlett’s test of sphericity” and “Kaiser-Meyer-Olkin” (KMO) were also conducted to check the data suitability for subsequent EFA. The recommended value for “Bartlett’s test of sphericity” should be $\rho < 0.01$, and the minimum suggested KMO value should be (0.60) (Field, 2013). In the present study, the KMO value obtained is 0.648. The initial analysis showed that the collected data from the industries are suitable for the EFA analysis. EFA can be used to determine the factor structure of variables using the varimax factor rotation (Field, 2013).

The CSFs were categorized into the four major groups, which shows the total variance of 72.62%. The range of factor loading for each challenge is between 0.6 and 0.9, which is above the acceptable value for analysis suggested in the literature. The first group was identified as “’Organizational Initiatives” – three CSFs, namely Top management support (C1), Prioritizing the lean tools and practices (C6) and Long term vision (C7). The second group was identified as “Knowledge and Technology Awareness” – three CSFs, namely Wi-Fi-enabled technologies (C2), L4.0 awareness (C5) and Machine-to-machine communication (M2M) (C11). The third group was identified as “Strategic Planning” – three CSFs namely Security of data and foolproof cybersecurity (C8), Strategy implementations (C9) and Funds/resource availability (C10) are classified. The fourth group identified is related to “Employee Engagement and Readiness”. Two CSFs, i.e. Employee training (C3) and Employee readiness for change (C4), are identified.

Table 2. Demographic profile

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

Source(s): Authors’ own work

Reliability checking is crucial for assessing the accuracy and "goodness" of a measure. Convergent validity is evaluated using the factor-loading concept, where a value greater than 0.5 is considered acceptable. Cronbach's alpha (α), a widely used measure of reliability, indicates the internal consistency of a scale. In this study, the overall Cronbach's alpha value is 0.768, which falls within the acceptable range.

The fuzzy DEMATEL procedure, as stated before, was applied systematically. DMs comprising five DMs were selected to provide the contextual relationship rating. A brainstorming session was conducted. DMs provided insights on various CSFs under consideration and explored their practical implications. A questionnaire comprising rating points was developed, and evaluations were obtained from field experts. DMs experience was from 7 to 17. Table 3 represents the summary of DMs.

The study utilized data inputs from field practitioners and academia, who provided ratings. The linguistic scale used in this conversion is represented in Table 4.

The aggregated feedback from *k* DMs was carried out and shown in Table 5.

Table 3. Summary of DMs

Expert (position)	Gender	Experience
Assistance manager	Male	7
Manufacturing head	Male	14
Section executives	Male	11
Section head	Female	16
Professor	Female	17

Source(s): Authors' own work

Table 4. The scale used in the FDEMATEL methodology

DM feedback	Description of the influence	TFN
1	No	(0.0, 0.1, 0.3)
2	Low	(0.1, 0.3, 0.5)
3	Medium	(0.3, 0.5, 0.7)
4	High	(0.5, 0.7, 0.9)
5	Max	(0.7, 0.9, 1.0)

Source(s): Authors' own work

Table 5. Initial direct relationship matrix

CSFs	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	Sum
C1	1.00	0.66	0.57	0.41	0.41	0.53	0.63	0.57	0.72	0.38	0.31	6.18
C2	0.50	1.00	0.47	0.50	0.60	0.41	0.50	0.56	0.48	0.47	0.50	6.00
C3	0.60	0.63	1.00	0.59	0.41	0.57	0.50	0.63	0.81	0.57	0.50	6.81
C4	0.41	0.44	0.81	1.00	0.69	0.57	0.41	0.53	0.72	0.63	0.69	6.90
C5	0.50	0.50	0.57	0.41	1.00	0.50	0.69	0.57	0.56	0.66	0.60	6.56
C6	0.59	0.56	0.53	0.50	0.47	1.00	0.41	0.56	0.76	0.63	0.60	6.62
C7	0.69	0.47	0.44	0.41	0.69	0.53	1.00	0.50	0.56	0.44	0.69	6.43
C8	0.60	0.56	0.50	0.41	0.63	0.81	0.53	1.00	0.63	0.47	0.50	6.65
C9	0.50	0.53	0.63	0.78	0.63	0.60	0.66	0.47	1.00	0.56	0.60	6.96
C10	0.41	0.56	0.56	0.60	0.47	0.41	0.47	0.38	0.69	1.00	0.69	6.24
C11	0.31	0.57	0.66	0.69	0.53	0.66	0.60	0.44	0.70	0.50	1.00	6.65

Source(s): Authors' own work

The aggregated matrix was normalized and shown in Table 6.

A total relationship matrix was derived from a normalized matrix and shown in Table 7.

Finally, the cause-and-effect relationship was calculated and depicted in Table 8. Based on the importance relationship, a causal interrelationship was constructed and depicted in Figure 2.

5. Managerial implication

The study offers significant theoretical and practical implications for the integration of L4.0 in SMEs. Theoretically, it provides a conceptual framework linking Lean principles with I4.0 technologies, advancing the understanding of CSFs specific to resource-constrained environments like SMEs. By addressing gaps in L4.0 literature, the research contributes to the interdisciplinary fields of Lean management, digital transformation and SME development. Practically, the findings offer actionable guidelines for SMEs to underline significant CSFs for successful L4.0 implementation, ensuring optimal resource allocation and minimizing risks. The study also provides a scalable roadmap to transition from traditional Lean practices to an L4.0 environment, helping SMEs enhance operational efficiency, reduce waste and improve competitiveness in the I4.0 era.

The study also classifies the identified CSFs into four groups, namely “Organizational Initiatives”, “Knowledge and Technology Awareness”, “Strategic Planning” and “Employee Engagement and Readiness”. The management may tale lead from these groups while implementing the L4.0 in I4.0 industries in the SMEs. The study identifies the L4.0 CSFs for practicing managers. The practicing managers may devise suitable strategies to control the CSF identified under each group to manage the smooth L4.0 implementation in SMEs. These insights bridge the gap between theory and practice, empowering practicing managers of SMEs to thrive in the evolving industrial landscape in accomplishing L4.0 implementation.

6. Conclusions, limitations and future research work

The research reveals CSFs and prioritizes them as being significant in implementing L4.0 in SMEs. By considering principles based on Lean among the I4.0 technologies, SMEs can eliminate non-value-adding activities, enhance operational efficiency and improve competitiveness. The findings highlight that Top Management Support and Commitment, Employee Training and Financial Capabilities are the most influential CSFs. These factors provide a strategic framework for SME leaders to address key challenges and ensure the successful adoption of L4.0.

Table 6. Normalized direct relation matrix (D)

CSFs	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
C1	0.14	0.09	0.08	0.06	0.06	0.08	0.09	0.08	0.10	0.05	0.05
C2	0.07	0.14	0.07	0.07	0.09	0.06	0.07	0.08	0.07	0.07	0.07
C3	0.09	0.09	0.14	0.09	0.06	0.08	0.07	0.09	0.12	0.08	0.07
C4	0.06	0.06	0.12	0.14	0.10	0.08	0.06	0.08	0.10	0.09	0.10
C5	0.07	0.07	0.08	0.06	0.14	0.07	0.10	0.08	0.08	0.09	0.09
C6	0.09	0.08	0.08	0.07	0.07	0.14	0.06	0.08	0.11	0.09	0.09
C7	0.10	0.07	0.06	0.06	0.10	0.08	0.14	0.07	0.08	0.06	0.10
C8	0.09	0.08	0.07	0.06	0.09	0.12	0.08	0.14	0.09	0.07	0.07
C9	0.07	0.08	0.09	0.11	0.09	0.09	0.09	0.07	0.14	0.08	0.09
C10	0.06	0.08	0.08	0.09	0.07	0.06	0.07	0.05	0.10	0.14	0.10
C11	0.05	0.08	0.09	0.10	0.08	0.09	0.09	0.06	0.10	0.07	0.14

Source(s): Authors’ own work

Table 7. Total relationship matrix

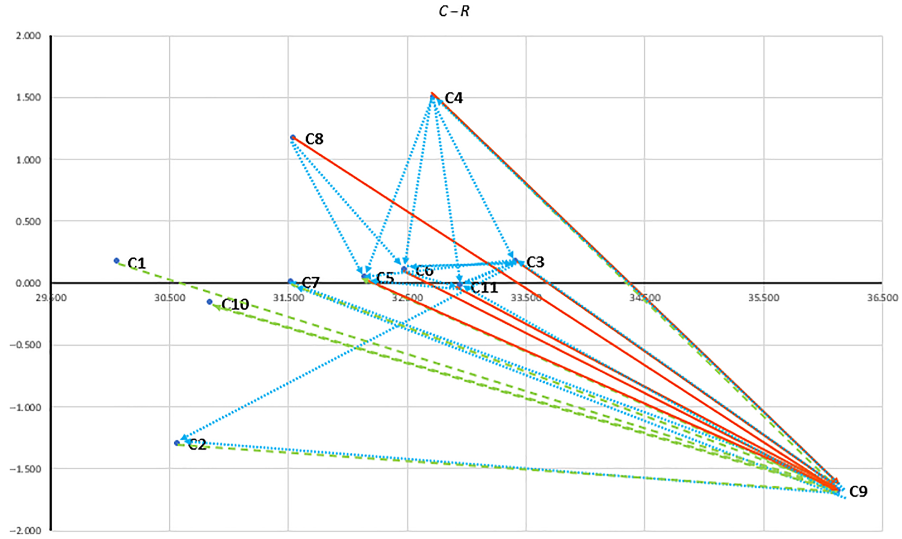
CSFs	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	D
C1	1.35	1.38	1.41	1.31	1.35	1.38	1.36	1.30	1.62	1.29	1.36	15.11
C2	1.23	1.39	1.36	1.28	1.34	1.31	1.30	1.26	1.54	1.27	1.35	14.63
C3	1.42	1.51	1.63	1.48	1.49	1.53	1.48	1.45	1.81	1.46	1.54	16.79
C4	1.41	1.51	1.63	1.57	1.56	1.55	1.49	1.46	1.83	1.50	1.60	17.11
C5	1.35	1.43	1.50	1.39	1.52	1.45	1.45	1.38	1.70	1.42	1.50	16.1
C6	1.38	1.46	1.51	1.42	1.45	1.55	1.42	1.40	1.75	1.43	1.51	16.29
C7	1.35	1.40	1.45	1.36	1.45	1.43	1.47	1.34	1.66	1.36	1.48	15.77
C8	1.39	1.47	1.51	1.41	1.49	1.53	1.45	1.47	1.73	1.41	1.50	16.36
C9	1.44	1.53	1.61	1.55	1.56	1.57	1.54	1.46	1.88	1.50	1.60	17.23
C10	1.27	1.38	1.44	1.36	1.37	1.37	1.35	1.29	1.64	1.41	1.45	15.34
C11	1.35	1.47	1.55	1.47	1.48	1.51	1.46	1.39	1.76	1.43	1.59	16.46
R	14.945	15.935	16.62	15.613	16.052	16.188	15.758	15.191	18.907	15.505	16.487	

Source(s): Authors' own work

Table 8. Importance relationship

CSFs	D	R	$D+R$	$D-R$	Cause/Effect
C1	15.114	14.945	30.059	0.169	Cause
C2	14.633	15.935	30.568	−1.302	Effect
C3	16.795	16.620	33.415	0.175	Cause
C4	17.115	15.613	32.727	1.502	Cause
C5	16.098	16.052	32.149	0.046	Cause
C6	16.291	16.188	32.480	0.103	Cause
C7	15.766	15.758	31.524	0.008	Cause
C8	16.362	15.191	31.553	1.171	Cause
C9	17.226	18.907	36.133	−1.681	Effect
C10	15.342	15.505	30.847	−0.164	Effect
C11	16.460	16.487	32.947	−0.027	Effect

Source(s): Authors' own work



Source(s): Authors' own work

Figure 2. Causal interrelationship

6.1 Limitations

The study focusing on the SMEs; hence, the generality of the results may have limited applicability to larger enterprises. The large enterprise may differ with significantly different operational dynamics. Additionally, the data collection was geographically and sectorally constrained, which may not meet the diversity of challenges and success factors across various regions or industries. The reliance on the FDEMATEL method, while effective in establishing interrelationships among CSFs, depends on expert judgment, which introduces a degree of subjectivity and potential bias in the analysis. The listed limitations may be carefully checked while undertaking the specific study.

6.2 Future research work

Future research could expand on this study by including a broader range of industries and geographical regions to ensure the generalizability of the findings. An attempt to explore the advanced technologies integration such as IoT, CC, etc. with L4.0 could provide deeper insights into their potential to address implementation challenges. Additionally, longitudinal studies could be conducted to assess the long-term impacts of the identified CSFs on operational performance and sustainability in SMEs. Further investigation into the intersection of L4.0 with environmental and sustainability practices could also offer valuable contributions to achieving economic and ecological goals in SMEs.

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