Final manuscript of:

An assessment of barriers to integrate Lean Six Sigma and Industry 4.0 in manufacturing environment: Case based approach

Sonu Rajak, National Institute of Technology, India

Prakash Kumar,National Institute of Technology, India

Aayush Modi,National Institute of Technology, India

Vikas Swarnakar, Khalifa University

Jiju Antony, Northumbria University

Michael Sony, Oxford Brookes University

An assessment of barriers to integrate Lean Six Sigma and Industry 4.0 in manufacturing environment: Case based approach

Abstract

The integration of Lean Six Sigma (LSS) with Industry 4.0 (I4.0) has numerous advantages for the organization such as enhancement of product and service quality, accurate forecasting in complex processes, and significant cost reduction. LSS and I4.0 integration in manufacturing environments face some challenges, including data integration, a lack of understanding of the strategic implications of integrating LSS and I4.0, security and data privacy issues, return on investment, and a shortage of consultants and trainers. In this context, this paper aims to analyse the barriers and their interrelationship that could hinder the manufacturing organisation from embracing LSS with I4.0. 15 potential barriers were identified from the literature review and by taking the opinion of experts and decision-makers. The grey decision-making trial and evaluation laboratory (DEMATEL) method was applied to find the influence of each barrier on other barriers. The cause-effect relationship between the barriers was identified and later validated by experts. Using a single case study methodology, this study prioritises the identified barriers that hinder the automotive component manufacturing industry from integrating LSS with I4.0. The top three barriers were "lack of long-term vision", "timely and accurate data availability", and "lack of automation". This paper will help the managers to better understand which barriers could affect the integration of LSS with I4.0. The identification and understanding of the relationship between LSS barriers is a novel contribution by offering a holistic perspective, synergy identification, mitigating risk of failure, and enhancing decision-making capabilities for LSS with I4.0 implementation.

Keywords: *Industry 4.0; Lean six-sigma; Barrier; Grey-DEMATEL; Smart manufacturing; Automotive Industry*

1 Introduction

Industry 4.0 is transforming the way companies manufacture their products. Newer technologies that include artificial intelligence (AI), internet of things (IoT), cyber security, cloud computing, cyber-physical system (CPS), and machine learning are integrated into their production process to minimize costs and improve overall quality of manufacturing and distribution of the product (Amjad *et al*., 2021; Tieng *et al*., 2022; Da Silva *et al*., 2020). Also, these advanced technologies are changing the workflows and production processes leading to effective control and digitised improvements. I4.0 is widely anticipated to bring a novel industrial era of new tools and technologies being unified for various digital solutions (Frank *et al*., 2019; Yadav *et al*., 2020a). For the last few years, companies have been using I4.0 as a strategic model to outperform their rivals and acquire an edge (Kolberg *et al*., 2017). It also works as a model for improvement in various metrics namely productivity, lead time, cost, quality, and customer satisfaction (Ghobakhloo & Fathi, 2019; Frank *et al*., 2019). These modern technologies are bringing a revolution in the entire manufacturing sector. These technologies are significantly improving productivity and quality which is beneficial for companies. Unquestionably, the automobile industry has also been dashing in the I4.0 revolutions. There are many benefits after the adoption of I4.0. Indian automotive companies have also started adopting new modern technologies but there is still a long way to go (Raj *et al*., 2020).

LSS aims to eliminate non-value-added activities, waste, and inefficiency in the production process and improve the overall quality and working conditions in order to provide a better response to the needs of customers (Yadav & Desai, 2016; Shukla *et al*., 2021; Zhu *et al*., 2020). The lean concept manages the removal of activities that are value-adding; it does not state the problems in regard to non-conformity and variation in products or processes (Ringen and Holtskog, 2013; Swarnakar *et al*., 2021). Simultaneously, Six Sigma reduces the variation in the interaction and decreases distortion or deformity in products and enterprises, but it can't get rid of activities that are not adding any value (Swarnakar and Vinodh, 2016; Alnadi & McLaughlin, 2021). The LSS integrates principles of lean in accordance with the five phases of six sigma for the improving organisation's operations (Patel & Patel, 2021; Prakash *et al*., 2021).

Although LSS and I4.0 have been used individually in industries, nowadays to take more competitive advantage, improve quality, and customer satisfaction, industries are integrating LSS with I4.0 (Yadav *et al*., 2020b Riley, Kovach & Carden, 2013). As a result of integrating LSS into I4.0, manufacturing companies can improve quality control and operational efficiency, become more competitive to the market, reduce costs, respond quickly to changing market demands, and make data-driven decisions (Pongboonchai-Empl *et al*., 2023). Still, there are many difficulties in the integration of both due to a lack of data or research in this field. The DMAIC ("Define-Measure-Analyse-Improve-Control") methodology and lean manufacturing concept are integrated with I4.0 to achieve higher quality, productivity, and flexibility in the industry. Integration of LSS with I4.0 also sometimes known as quality promises to solve futuristic challenges toward achieving operational excellence. The integration of LSS with I4.0 is a highly debated topic these days in literature; however, companies are keen to integrate these approaches to improve quality, enhance forecasts, and minimize cost (Yadav & Desai, 2017; Yadav *et al*., 2020b). The integration of LSS with I4.0 is not easy as several hurdles and challenges those hurdles should be known to industrial managers and planners for effective integration of these approaches (Amjad *et al*., 2021). Due to a lack of understanding and knowledge about these hurdles, organisational managers still struggle to integrate the LSS and I4.0 successfully in their organisation (Frank *et al*., 2019; Yadav *et al*., 2020b). A detailed understanding of barriers affecting the integration of these approaches could help to integrate them properly.

For manufacturing companies, it is somewhat challenging to comprehend and recognize the barriers that affect the integration of LSS and I4.0 approaches. Therefore, only those leading barriers affecting these integration processes should be identified and prioritised for effective consideration based on their priority. There are very few published studies that reported barriers related integration of LSS and I4.0. Khanzode *et al*. (2021) have applied the DEMATEL to recognise and prioritise the barriers to integrating LSS and I4.0 pertaining to the circular economy. Letchumanan *et al*. (2022) used the principal component factor analysis method to identify and evaluate the factor enabling the green LSS in the Era of I4.0 However, any of these studies have not analysed the cause-effect relationship among the barriers, which indicates a need to analyse the cause-and-effect relationship among those leading barriers to address inappropriate or inaccurate human judgments for effective integration of LSS and I4.0 technology. Based on the inference of these gaps, it can be concluded that a systematic evaluation of barriers can be performed in manufacturing companies to provide a clear roadmap to integrate LSS with I4.0.

The current study addresses the following research objectives:

RG1: *Identify barriers that affect the integration of LSS with I4.0 in manufacturing industries.*

RG2: *Identify inter-relationship among those barriers.*

RG3: *Prioritise those barriers affecting the integration of LSS and I4.0.*

To address all these research goals this study analyses the barriers to the integration of LSS with I4.0 in the automobile industry. In this context, various barriers were identified through a comprehensive analysis of literature and discussion with various industry experts. After the collection of data from different industry experts, barriers were analysed using the Grey-DEMATEL method.

The paper is organised as follows: Section 2 provides a literature review on the integration of LSS and I4.0, including discussions on the barriers to integration, and the application of the multi-criteria decision-making (MCDM) approach to analyse interrelationships, as well as highlighting research gaps. Section 3 presents the methodology used in the study. Section 4 presents a case study illustrating the application of the methodology. The results of the study are discussed in Section 5, which also includes theoretical and managerial implications of the findings. Finally, Section 6 concludes the paper and suggests future research directions.

2 Literature Review

A detailed review of the literature was performed on the topic of LSS and I4.0 to identify the barriers to LSS and I4.0. The following keywords were used: 'Lean Six Sigma', 'Industry 4.0', 'Lean Six Sigma 4.0', 'Lean Six Sigma 4.0 barriers', and 'MCDM techniques', from several databases including 'Web of Science', 'Scopus, Science Direct', 'Google Scholar', 'Emerald', 'Springer', 'Taylor & Francis', etc. Articles were initially screened and selected based on the title and abstract. The literature review methodology is given in Figure 1. A detailed literature review was performed on the integration of LSS with I4.0, LSS, and I4.0 barriers, and the application of MCDM techniques in interrelationship development. In addition, research gaps are identified based on the findings of the review.

<<<<<<<<<<<Insert Figure 1 here>>>>>>>>>>

2.1 Integration of LSS with I4.0

The integration of LSS with I4.0 can bring some ground breaking changes to the industry. However, there are very few studies that have discussed the integration and implementation of combined LSS and I4.0 in organisations (Yadav *et al*., 2021). One such study is Chiarini & Kumar (2021) That investigates the possibility of combining LSS principles, tools, and techniques with I4.0 technologies. The goal was to use grounded theory methods to create a new pattern for operational excellence. Their research is initially a qualitative investigation based on interviews with experts from different manufacturing companies that have implemented LSS with I4.0. Further, Mrugalska & Wyrwicka (2017) investigated the co-existence of lean production and I4.0. The study by Pereira *et al*. (2019) discusses how I4.0 technologies can enhance lean production, especially through the use of connected sensor systems, Industrial Internet of Things (IIoT), IoT, big data, data analytics, cloud manufacturing, and additive manufacturing. Lean practices such as just-in-time (JIT) require accurate and timely information sharing, and this can be easily achieved by I4.0 (Buer *et al*., 2018). More recently, Saxby *et al.* (2020) tried to show the results of an evaluation on how lean management principles are going to help the implementation of I4.0 to continuously progress. Moreover, Raji *et al*. (2021) examined the extent to which I4.0 technologies allow lean and agile methods to be implemented in an organisation. Their study also examined, how the integration of I4.0 and supply chain operations may enhance performance improvement.

Some papers have analysed and discussed the barriers, methods, and tools of LSS in smart manufacturing and smart factory. Anvari *et al*. (2020) discussed the tool and techniques of LSS to measure the performance of smart factory. The study presented preliminary results of ongoing LSS research in smart factories and concluded that LSS and I4.0 are mutually beneficial. In the study, several perspectives are offered on how to improve the LSS methodology to achieve a more agile, integrated, efficient, and intelligent approach for continuous improvement across smart factories. A smart factory based on CPS was developed by Chen *et al.* (2020) by combining virtual and real mapping, big data, virtualisation, digital twin, and edge-to-cloud service technology.

2.2 Lean Six-Sigma and I4.0 Barriers

Although the successful implementation of LSS tools and techniques has provided enormous benefits to organisations. Whereas I4.0 integrates different digital technologies including IoT, CPS, data science, machine learning, and cloud computing to provide real-time data for manufacturing as well as service sectors (Frank *et al*., 2019). The studies by Nordin *et al.* (2010) and Ali *et al.* (2021b) have verified that many small & medium enterprises are not successfully implementing LSS in their organisations. On the other hand, the adoption of I4.0 technologies is still in its infancy in the Indian manufacturing and service sectors. Industries face several challenges in the adoption of I4.0 tools. Therefore, a comprehensive analysis of the barriers to LSS and I4.0 is required for successful adoption. According to Ali *et al*., (2021b) and Swarnakar *et al*., (2021), barriers affect the implementation of LSS in any organisation; thus, knowledge about the barriers is essential. Therefore, the identification of barriers before LSS implementation is essential. In this context, Rathi *et al.* (2021) identified impediments that automobile component manufacturing companies experience. Initially, they identified 31 LSS barriers found through a detailed review of articles and surveys. At the outset of the study, 31 LSS barriers were found by the authors, however, 17 were chosen following statistical analysis. Raval *et al.* (2021) presented various problems in an LSS implementation; vital key influencing factors for LSS deployment were analysed using the

Fuzzy-DEMATEL methodology. Similarly, Singh *et al.* (2019) identified 26 LSS barriers based on expert opinion. They explored the barriers of LSS and built interrelationships between them using interpretive structural modeling (ISM), and further driving and dependency power were analysed using the MICMAC (cross-impact matrix multiplication applied to classification) method. Yadav & Desai (2017) proposed 27 critical barriers to LSS implementation in an organisation. The "fuzzy-analytical hierarchy process (F-AHP)" method was used to develop a hierarchy of these barriers that ultimately helps practitioners to focus on the most causal factors that are influential. The identification of barriers provides insight into the major problems present in the industry that affect the implementation of LSS programs.

A few authors have studied the barriers to smart manufacturing and smart factory (Li *et al.*, 2019; Narwane *et al.*, 2022; Xing *et al.*, 2022). The concept of a smart factory pertains to factories using I4.0 technology to optimise manufacturing processes. It facilitates autonomous and optimised manufacturing processes by utilising cutting-edge technologies like robotics, sensors, and AI. Narwane *et al.* (2022) analysed the challenges to smart manufacturing for the micro, small & medium enterprises (MSME). The barriers were analysed by adoping the fuzzy-DEMATEL method. Critical barriers to the implementation of big data in smart factories are analysed by Li *et al.*, 2019 and Xing *et al.*, 2022. The barriers were categorised into six parts namely data-related, technical-related, technical support-related, social perspective, organizational-related, and individual barriers. Even though the terms I4.0 and smart factory sound similar, they have some differences. I4.0 is a broader term, refers to the creation of a highly automated and connected production environment where people, machines, and products are able interact, communicate, and work together in real-time.

Raj *et al.* (2020) examined the barriers to the implementation of I4.0 technology in the manufacturing field. Fifteen barriers were extracted through literature and consultations with industry experts. Further, these barriers were examined using a Grey-DEMATEL method from the viewpoints of developed and developing nations. The barriers were divided into three categories namely influencing, prominent, and resultant barriers. Nimawat & Gidwani (2021) have examined the hurdles to I4.0 implementation. The DEMATEL technique was applied to analyse the barriers. The findings of the study highlighted various fundamental barriers to the implementation of I4.0 and their causal relationships. Further, Karadayi-Usta (2020) identified the barriers that affect I4.0 adoption in organisations and evaluated these obstacles after getting insights from different experts. The study used ISM and MICMAC approaches to further analyse those barriers. A summary of the barriers identified from the literature related to LSS and I4.0 adoption is presented in Table 1.

<<<<<<<<<<<Insert Table 1 here>>>>>>>>>>

2.3 Application of MCDM in interrelationship development of factors

Defining the impact of each factor on the system can be difficult due to the complex interrelationship between factors in any system (Vinodh, S., & Swarnakar, 2015; Rajak *et al*., 2021a). When dealing with a complex situation, MCDM methods are the most effective way to identify the most influential factors (Chandra *et al*., 2022). Several MCDM methods have existed that are used to prioritise the factors. But, a hierarchical model needs to be developed to determine the contextual interrelationships between factors. Three MCDM approaches such as “ISM”, “DEMATEL”, and “fuzzy cognition map (FCM)”, and their various hybrid forms are normally used to develop structured hierarchical models. The main limitation of ISM over the other two MCDM methods include (i) Assessment is based on only one expert input and (ii) Although it can identify the interrelationships between factors, it cannot prioritise them. The following limitations apply to FCM in comparison with other approaches: (i) The results are difficult to understand in absolute terms, and all factors cannot be considered and (ii) Techniques for semi-quantification are not highly organised. As a solution for overcoming the above limitations, Grey-DEMATEL can be used. DEMATEL is an MCDM technique used to investigate the inter-relationship among the factors as well as help prioritise the factors (Yadav *et al*., 2020a). The DEMATEL technique can be combined with grey or fuzzy theory for better analysis. Grey theory removes the uncertainty, vagueness, and ambiguity from the input data that is always present while taking responses from experts (Si *et al*., 2018). Also, grey theory can be integrated with other techniques to minimize errors in human judgment (Tseng, 2009). Thus, Grey-DEMATEL provides better insights and solutions when compared with other MCDM techniques such as ISM and FCM. Further, Table 2 summarizes the differences between these approaches.

<<<<<<<<<<<Insert Table 2 here>>>>>>>>>>

The “DEMATEL” identifies the cause-effect relationship and the “grey theory” accounts for the error in human judgments (Rajak *et al*., 2021b). The DEMATEL has been used in several LSS and I4.0 studies. Raj *et al*. (2020) implemented the “Grey-DEMATEL” approach to examine the obstacles in the application of I4.0 technology to the manufacturing sector. Grey-DEMATEL has been applied to different applications such as healthcare (Kirkire & Rane, 2017), supply chain management (Aggarwal & Srivastava, 2019), and logistics and transportation (Dwivedi *et al*., 2021; Rajak *et al*., 2021b). Gupta *et al*. (2019) developed a six sigma deployment framework for MSME. Their proposed framework integrates the DEMATEL with other statistical and quality management tools.

2.4 Research Gap

I4.0 technology induces amazing improvements in the industrial sectors due to automation, flexibility, and sustainability. A few papers have analysed LSS enablers and barriers for the manufacturing and automotive sectors. But now, industries are trying to integrate LSS with I4.0 for better quality, and productivity improvement. However, it has been found that there is very limited evidence that describes the integration of LSS with I4.0. Many studies report the implementation of MCDM techniques that are used in LSS and I4.0 domains individually. A few studies have analysed various barriers to integrating lean production and I4.0. Further, there is limited research on the barriers to LSS and I4.0. Previous studies have used “ISM and MICMAC” approaches for the analysis of barriers that present direct or indirect relationships among the identified factors, but the “Grey-DEMATEL” approach can be applied which helps find the cause-effect relationship among the barriers and tries to address inappropriate or inaccurate human judgments. Based on the above-discussed gaps, it can be concluded that there is a need for proper investigation of barriers that affect the integration of I4.0 and LSS for a structured adoption in the automobile sector.

3 Methodology

The methodology for this research comprises different stages for analysing the barriers to the integration of LSS and I4.0 in the manufacturing industry. In the first stage, a literature review to understand the barriers to integrating LSS and I4.0 for manufacturing organisations has been performed, followed by detailed discussions with subject matter experts. In the next stage, subject matter experts were asked to provide specific inputs on the relationship among the identified barriers. A different “initial direct-relationship matrix” was formed with the help of the different expert responses. In the final (last) stage, subsequent steps of “Grey-DEMATEL” were followed to analyse the barriers. The results were then verified by the experts. Thus, the causal barriers that are the major reason for the complexity of integrating

LSS and I4.0 are found using the Grey-DEMATEL approach. Figure 2 highlights the detailed roadmap and steps followed in the study.

<<<<<<<<<<<Insert Figure 2 here>>>>>>>>>>

3.1 Identification and finalisation of Barriers

Barriers were identified from the literature relevant to the study. After reviewing all the relevant studies from different databases (database details are discussed in section 2), 15 potential barriers were identified and presented to the experts. We tried to contact recognised industry experts and result in four experts agreed to participate in the study. All experts have a vast understanding of LSS and I4.0 approaches. First of all, the experts were given a general understanding of these barriers by providing them with an in-depth explanation of each barrier during the personal interviews. The meeting was then conducted with a group of four experts for brainstorming sessions. And a total of 15 barriers are finalised in the meeting. Details of identified barriers are provided in Table 3. In addition, barriers are categorised with the assistance of experts and decision-makers. 15 barriers are categorised into five parts namely, 'Strategic decision (SD)', 'I4.0 technology (IT)', 'Economic (EC)', 'Integration (IG)', and 'Manufacturing strategy (MS)'. Categorisation of the identified barriers is shown in Figure 3. After a detailed discussion with the experts, the initial direct-relationship matrices were also formed which were then subsequently used for Grey-DEMATEL analysis.

<<<<<<<<<<<Insert Table 3 here>>>>>>>>>>

<<<<<<<<<<<Insert Figure 3 here>>>>>>>>>>

3.2 Grey-DEMATEL Approach

The Grey-DEMATEL method combines the grey system theory with the DEMATEL technique to analyse cause-effect relationships. The grey theory is particularly useful when dealing with vague, imprecise, or incomplete information (Xia *et al.*, 2015; Rajak *et al.*, 2021b). Compared to the fuzzy set theory, Grey-DEMATEL has the advantage of being adaptable in pattern detection, even with limited data (Yang & John, 2003). Grey-DEMATEL is effective in situations that consist of small teams made up of experts (Bai & Sarkis, 2013; Raj *et al.*, 2020). Bai & Sarkis (2013) and Raj et al. (2020) both used three and four members of the expert team, respectively in their study. Therefore, in this case study, the Grey-DEMATEL method is utilised to identify the cause-effect relationship between barriers. The subsequent steps outline the procedure for applying the Grey-DEMATEL method.

Step 1: Computing the initial relation matrices

Let's say there are *K* experts and *n* represents the "number of identified barriers". These *K* experts are asked to give their views on the relationships between the barriers. Based on their inputs, Initial relation matrices are computed where "the direct influence of factor *i* over factor *j"*, is evaluated on a linguistic scale of "*n* barriers": where a score of *N* represents "No influence", *VL* represents "Very Low influence", *L* represents "Low influence", *M* represents "Medium influence", *H* represents "High influence", and *VH* indicates a "Very High influence". Thus, "*k* initial relation matrices" are formed.

Step 2: Computing the grey-relation matrix

The above values are now converted to a grey scale. The grey values are represented by two values "higher and lower limit", as given in Equation 1:

$$X_{ij}^{k} = (u_{ij}^{k}, v_{ij}^{k}) \quad (1)$$

Where u_{ij}^{k} has represented the "lower limit" of grey values whereas v_{ij}^{k} represents "upper limit" of grey values for experts k^{th} signifying the relation between factors "*i* and *j"*. The grey scale used in this study is given in Table 4.

<<<<<<<<<<<Insert Table 4 here>>>>>>>>>>

Step 3: Computation of "average grey-relation matrix"

The "average grey-relation matrix" (A) is calculated by taking an average of all "grey-relation matrices". It can be calculated using the formulae given in Equations (2) & (3).

$$a_{ij}^{K} = \left(\frac{\sum_{k=1}^{K} u_{ij}^{k}}{K}, \frac{\sum_{k=1}^{K} v_{ij}^{k}}{K}\right) \quad (2)$$

$$A = \left[a_{ij}^{K}\right] \quad (3)$$

Step 4: Determining the crisp-relation matrix (Z)

This study uses a modified version of the CFCS (Converting fuzzy values into crisp scores) method to obtain the crisp values (Xia *et al*., 2015; Rajak *et al*., 2021). They are calculated in three steps:

1) Normalization

$$u_{ij}^{k} = \frac{u_{ij}^{k} - \min_{j} u_{ij}^{k}}{\Delta_{min}^{max}} \tag{4}$$

$$v_{ij}^{k} = \frac{v_{ij}^{k} - \min_{j} v_{ij}^{k}}{\Delta_{min}^{max}} \tag{5}$$

Here,

$$\Delta_{min}^{max} = \max_{j} v_{ij}^{k} - \min_{j} u_{ij}^{k} \tag{6}$$

2) Computing total normalized crisp values

$$Y_{ij}^{k} = \left(\frac{u_{ij}^{k}\left(1-u_{ij}^{k}\right) + \left(v_{ij}^{k} \times v_{ij}^{k}\right)}{\left(1-u_{ij}^{k} + \left(1-v_{ij}^{k}\right)\right)} \right) \tag{7}$$

3) Determining final crisp values

$$z_{ij}^{k} = \left(\min_{j} u_{ij}^{k} + \left(Y_{ij}^{k} \times \Delta_{min}^{max}\right) \right) \tag{8}$$

And,

$$Z = \left[z_{ij}^{K}\right] \tag{9}$$

Step 5: Determination of the normalized direct crisp-relation matrix (X)

Calculation of the "normalized direct relation matrix" is done using Equations (10) & (11).

$$S = \frac{1}{\max_{1 \le i \le n} \left(\sum_{j=1}^{n} z_{ij}\right)} \quad (i, j = 1,2,3, \ldots\ldots, n) \tag{10}$$

And,

$$X = S \times Z \tag{11}$$

Each value in matrix *X* lies between the range of 0 and 1.

Step 6: Determination of the total-relation matrix (T)

Determination of the "total-relation matrix" was done using Equation (12).

$$T = X(I - X)^{-1} \tag{12}$$

Here, *I* represent "identity matrix"

Step 7: Evaluate the sum of rows and columns in the total relation matrix

The "sum of rows" is denoted by R_i and the "sum of columns" is denoted as D_j within the "total-relation matrix" (T). Formulas to compute this are given in Equation (13).

$$R_i = \left[\sum_{j=1}^{n} T_{ij}\right] \forall\, i \quad and \quad D_j = \left[\sum_{j=1}^{n} T_{ij}\right] \forall\, j \tag{13}$$

Step 8: Calculation of the overall prominence (P_i) and the net effect (E_i)

Formulas for computing "overall prominence (P_i)" and the "net effect (E_i)" are given in Equations (14) and (15).

$$P_i = \left[R_i + D_j\right] \forall\, i = j \tag{14}$$

$$R_i = \left[R_i - D_j\right] \forall\, i = j \tag{15}$$

Step 9: Computing the causal diagram or digraph.

The causal diagram or the cause-effect digraph was built by the "horizontal axis" as overall prominence (*D*+*R*). The "vertical axis (*D*-*R*)" represents the net effect. Diagraph can be computed using the dataset of "(*D*+*R*, *D*-*R*)", where the "horizontal axis (*D*+*R*)" is calculated by adding *D* and *R*, and the "vertical axis (*D*-*R*)" is calculated by subtracting *R* from *D*.

4 A real-case application

Case studies can be used for theory generation and theory elaboration (Ketokivi & Choi, 2014). In this study, a single case study to analyse these barriers in the automotive manufacturing industry is discussed to validate the benefits of integrating LSS and I4.0. In case study research, it may be useful to study multiple cases to undertake across the case analysis (Eisenhardt, 1989). But, a single case study is preferred when the study wants to explore beneath the surface for in-depth analysis (Voss *et al.*, 2002). The single case is further useful for "*new exploratory investigations*", which can result in thought provoking insights (Meredith, 1998, p. 451). Further major insights have been obtained from single case studies (McCutcheon and Meredith, 1993, p. 247). In this study, a single case study is used because (i) identify the barriers in a real-life context, (ii) identify the relationships between the barriers. (iii) Prioritise those barriers affecting the integration of LSS and I4.0 in a real-life context. While using a single case study approach identification of case is a crucial aspect. A case is selected that tells the best story with respect to the objectives of the study (Dyer and Wilkins, 1991). Further, the case should be a talking pig and include sufficient variation in the context of study (Siggelkow 2007; Yin, 2014). The case study was conducted in Indian based automotive manufacturing company located in the state of Tamil Nadu, India.

The case industry manufactures automotive components such as sensors, switches, and control devices, solenoids, and electromechanical assemblies. The company has already implemented lean, six sigma, and sustainability practices, and now are keen on integrating them with I4.0. The company has tried to automate and digitalize its production line and supervise, and control with the help of efficient software systems. These software systems are able to collect real-time information based on which managers may be able to plan systematically. This leads to better communication and improved productivity with superior quality.

For efficient implementation of LSS with I4.0, the very first task was to identify the barriers because without proper understanding and knowledge of relevant barriers and their effect on its adoption may have more chances of failure. Hence, to mitigate the implementation failure, this study initially identified the barriers which affect the implementation process of LSS and I4.0. For this, a questionnaire was developed and forwarded to the subject matter experts. This study was conducted with the assistance of four experts. All the four experts are the decision makers for the case organisation. The experts are all highly experienced with more than 20 years of experience in areas such as lean manufacturing, six sigma, automation, I4.0, total quality management, quality 4.0, and sustainable manufacturing. The details of the four experts who participated in the study are shown in Table 5. After the responses from the experts, the Grey-DEMATEL method was applied to analyse the cause-effect relationship among the barriers.

<<<<<<<<<<<Insert Table 5 here>>>>>>>>>>

The analysis of these barriers helps the manager to find out the most causal barriers and subsequently find out the solutions to deal with them. Many industries are not able to enjoy the benefits of LSS and I4.0 implementation because of the inefficient integration of both (Bhat *et al*., 2020). Thus, analysis of these barriers is important for the efficient implementation of LSS in integration with I4.0. The application of the case study is illustrated in the subsequent steps:

Step 1: Barriers to the integration of LSS and I4.0 are identified by a comprehensive literature review and experts opinions. Then, the industrial experts were asked to give a direct relationship among the barriers on a “linguistic scale” as shown in Table 6. The relationship shows the influence of a barrier over another barrier, and it may range from “No influence” to

"Very High influence". The 15×15 direct-relation matrices obtained from the expert contain linguistic data.

<<<<<<<<<<<Insert Table 6 here>>>>>>>>>>

Step 2: Initial grey-relation matrices are then computed from the direct relation matrices using the grey-scale conversion. In this study, the number of experts was four, therefore, a total of four gray-relation matrices are then developed.

Step 3: "Average grey relation matrix (*A*)" is computed in this step using the formula given in Eq. (2) and (3). Equal weights were assigned to each matrix and the average of the "initial grey relation matrix" is computed and shown in Table 7.

<<<<<<<<<<<Insert Table 7 here>>>>>>>>>>

Step 4: "Crisp grey relation matrix (*Z*)" is now calculated in steps using the formulas given in Eq. (4)-(9) and given in Table 8.

<<<<<<<<<<<Insert Table 8 here>>>>>>>>>>

Step 5: After computing the crisp grey relation matrix (*Z*), normaliee it to obtain the "normalised crisp grey relation matrix (*X*)". The Formula to compute it is shown in Eq. (10) and (11) and the matrix is represented in Table 9.

<<<<<<<<<<<Insert Table 9 here>>>>>>>>>>

Step 6: "Total relation matrix (*T*)" is calculated from "normalized crisp grey relation matrix" using Eq. (12). It is represented in Table 10.

<<<<<<<<<<<Insert Table 10 here>>>>>>>>>>

Step 7: The row sum (R_i) and column sum (D_j) are identified in this step using Eq. (13) for each row and column of the "total relation matrix (*T*)". These values are represented in Table 11.

Step 8: Overall prominence (P_i) and net effect (R_i) are calculated in this step. It can be calculated using Eq. (14) and (15). These values are also shown in Table 11.

<<<<<<<<<<<Insert Table 11 here>>>>>>>>>>

Step 9: Finally, a digraph is formed using the data from Table 11, where overall prominence (P_i) is represented on the "horizontal axis" and net effect (R_i) is represented on the "vertical

axis". The cause-effect relationship is identified and visualised in the digraph. The digraph is given in Figure 4.

<<<<<<<<<<<Insert Figure 4 here>>>>>>>>>>

5 Results and analysis

This section presents the results of barrier analysis based on the grey-DEMATEL technique. The greater value of overall prominence ($R+D$) of a barrier shows the total influence which exert or receive with respect to other barriers. On the other hand, the "net effect (R - D) value" tells us about the influence that a barrier exerts over other barriers. If the value of the net effect is "positive or greater than zero", then the barrier has more influence over other barriers (i.e., causal barriers) and if the value is "negative", then it represents that the barrier is more influenced by other barriers (i.e., effect barriers). Based on the values of "overall prominence ($R+D$) and net effect ($R-D$)" from Table 11; the barriers can be categorised into three categories such as "prominent barrier", "causal barrier", and "effective or resulting barrier". The subsections below provide an elaborate description of the categories.

5.1 Prominent Barriers

These are the barriers that are highly related to other barriers i.e., these barriers can highly impact other barriers. Thus, these barriers must be dealt with systematically so that they don't affect other barriers. The barriers with higher values of ($R+D$) are more prominent than others. The barriers are prioritised based on ($R + D$) values as follows: LSS2 > LSS15 > LSS7 > LSS6 > LSS14 > LSS8 > LSS11 > LSS3 > LSS5 > LSS10 > LSS13 > LSS12 > LSS4 > LSS9 > LSS1. Based on the result, the five barriers that are most prominent based on their ($R + D$) value are "Lack of long-term vision", "Timely and accurate data availability", "Lack of Automation", "Lack of funds/resource availability" and "Inefficient use of data analysis and prediction system". "Lack of long-term vision" comes out to be the most prominent barrier and experts also supported this outcome. Further, the "Lack of long-term vision" is a top management-related barrier. First of all, top management should have a vision for integrating LSS with I4.0. All the major changes in production methods, activities, processes, and principles for the integration of LSS with I4.0 are top management driven. This outcome is aligned with Zhang *et al*.'s (2017) study. "Timely and accurate data availability" is the key tool for I4.0 implementation. There is always a need for data exchange through IoT, and cloud computing in the automotive manufacturing industry for creating a smart factory. This finding is concurrent with Gutierrez *et al*. (2016) and Yadav *et al*. (2021) study. Automation is essential for the successful adoption of LSS and I4.0. Automation is the base of I4.0 and directly helps in designing the LSS and I4.0 implementation framework successfully. This outcome is also supported by Chiarini & Kumar's (2021) study. The initial investment for the adoption of LSS with I4.0 is rather high due to the renewal of information technology infrastructure, and the implementation of enterprise resource planning solutions. Similar findings are consistent with Ghobakhloo & Fathi's, (2019) study. Data analysis is the most important factor for reducing the variability of the product and process and also improving the overall quality of the organisation. These findings are aligned with Ambekar & Hudnurkar, (2017) and Sony's (2020) study. Prominent barriers will most probably affect our decision on other barriers therefore these barriers must be resolved so that a smooth integration of LSS and I4.0 can be achieved.

5.2 Causal Barriers

Causal barriers are the barriers that have a high influence on the effect barriers. These barriers must be resolved before the effect barriers as they have a higher impact on the integration of LSS and I4.0. The barriers above the X-axis (Figure 4) have a high influence on the implementation of LSS with I4.0 and are placed in a causal or influential group. The top five barriers with the highest positive (*R* - *D*) value are "Scarcity of trainers and consultants in the sector from managers", "Insufficient supervision from top management", "Ineffective project management", and "Inefficient software systems such as MES/SCADA" and "Disproportion between customer demands and company priorities". Experts agree that the "Scarcity of trainers and consultants in the sector" can be one of the most important factors since stakeholders with a complete understanding of LSS and I4.0 is essential for their smooth integration. This result is aligned with Gandhi *et al*.'s (2021) outcomes which stated that for the successful implementation of any new strategy, trainers and consultants are required. "Insufficient supervision from top management" will affect productivity and also for the successful operation of any strategy supervision from the top management and managers are important. These findings are concurrent with Ali *et al.'s* (2021a) results. "Ineffective project management" may lead to low team morale, stakeholders' dissatisfaction, budget overruns, and the industry at risk. Similar findings were concluded in the study by Sreedharan & Sunder (2018). To improve manufacturing process quality, an "Efficient software system such as MES/SCADA" is required. It tracks the shop floor activity to make changes in processes, and equipment to improve workers safety and production process. These findings are consistent with Chiarini & Kumar's (2021) study. "Disproportion between customer demands and company priorities" is also an important barrier to the implementation of LSS with I4.0. These barriers must be resolved before the effect barriers because their impact value is more, and they can cause major problems in the unification of LSS and I4.0.

5.3 Effect Barriers

These barriers are most influenced by other barriers and placed below the X-axis in effect or the resulting group (Figure 4). These barriers are determined by negative (R – D) value. The top five effect barriers based on (R – D) value are "Lack of Automation", "Difficulties in the collection of data for LSS deployment", "Timely and Accurate Data Availability", "Lack of long-term vision" and "Precise identification of the processes and activities that is specialized and repeatable".Industries are facing significant difficulties in the collection of good-quality data. Data collection has key role in quality and productivity improvement. "Precise identification of the processes and activities that are specialized and repeatable" is the basic level of implementation of LSS with I4.0. Specialized and repeatable processess can be easily automated with IoT, AI, and machine learning to give focus to other value-added activities. These findings are similar to Chiarini & Kumar's (2021) analysis of barriers from the perspective of Italian manufacturing companies.

5.4 Interrelationship among sub barriers

The cause-effect relationship between the barriers is discussed in sections 5.1 to 5.3 and shown in Figure 4. Further, for better clarity, these barriers are categorised into five parts (Figure 3). Cause-effect relationship for strategic decision barriers is shown in Figure 5. The result shows that "Insufficient supervision from top management" is a cause barrier whereas, "Lack of long-term vision" and "Timely and accurate data availability" are the effect barriers. Figure 5 illustrates that each barrier pair is interconnected by the arrow. The availability of timely and accurate information and data is the backbone of I4.0 integration. It was examined with the case organisation and found that organisation was struggling to get accurate and timely data because of insufficient supervision from the top management. However, "Lack of long-term vision" is dependent upon another cause barrier "Lack of understanding of the strategic significance of integrating LSS and I4.0".

<<<<<<<<<<<Insert Figure 5 here>>>>>>>>>>

Cause-effect relationship for I4.0 technology barriers is shown in Figure 6. The result shows that “Inefficient software systems such as MES/SCADA” and “Inefficient use of data analysis and prediction system” are cause barriers whereas, ‘lack of automation’ is the effect barrier. Figure 6 shows barriers “Lack of automation” and “Inefficient software systems such as MES/SCADA” holds a mutual relationship and “Inefficient use of data analysis and prediction system” affect automation. The case organisation identifies the need for robust software like MES/SCADA in order to control its shop floor activities. It will connect all activities related to production in a streamline and ensure smooth production. It facilitates the real-time conversion of raw materials into finished products including scheduling, tracking, and tracing products and materials, controlling the statistical process of production, dispatching, maintaining the overall equipment effectiveness and downtime, preventive maintenance, monitoring machine health, and analyses the performance of the production system.

<<<<<<<<<<<Insert Figure 6 here>>>>>>>>>>

Cause-effect relationship for economic-related barriers is shown in Figure 7. The result shows that “Economic benefits are not clearly defined” and “Lack of funds/ resource availability” are cause barriers. But, there is no relationship between the barriers. Knowledge of economic benefits can motivate top management the implementation of LSS with I4.0. In the discussion with the top management of the case organisation, they agreed to conduct the cost-benefit analysis.

<<<<<<<<<<<Insert Figure 7 here>>>>>>>>>>

Cause-effect relationship for Integration-related barriers is given in Figure 8. The result reveals that “Scarcity of trainers and consultants in the sector” and “Lack of understanding of the strategic significance of integrating LSS and I4.0” are cause barriers whereas, “Difficulties in data collection for LSS deployment” is the prominent effect barrier. All the stakeholders of the organisation are not aware of the strategic significance of integrating LSS with I4.0 due to the lack of trainers and consultants in the sector. Consequently, the case organisation is experiencing difficulty collecting data for LSS – I4.0 deployment. Based on discussions with the organisation's top management, training is now being provided for all stakeholders to understand automation, I4.0, concept of smart factory, and benefits of integrating LSS with I4.0.

<<<<<<<<<<<Insert Figure 8 here>>>>>>>>>>

Cause-effect relationship for manufacturing strategy barriers is shown in Figure 9. The result shows that “Ineffective material handling and transportation”, “Disproportion between customer demands and company priorities”, and “Ineffective project management” are cause barriers whereas, “Precise processes and activities identification which is specialized and repeatable” is the effect barrier. Figure 9 reveals that there is no relationship between barriers “Precise processes and activities identification which is specialized and repeatable” and “Ineffective material handling and transportation” whereas the barriers “Disproportion between customer demands and company priorities” and “Ineffective project management” have the mutual relationship. “Ineffective project/ production management” leads to a “Disproportion between customer demands and company priorities”.

<<<<<<<<<<<Insert Figure 9 here>>>>>>>>>>

5.5 Sensitivity Analysis

A “sensitivity analysis” is conducted to check the credibility of the results. Different weights were assigned to initial relation matrices of different experts and checked for any difference from the original results. For sensitivity analysis, “different weights” assigned to the relational scores of different experts. In the original conditions, all the experts were given the same weights but during the sensitivity analysis, one expert is given more weight than the other three experts. This is done for each expert and the results were compared with the original scenario. For example, in the first sensitivity analysis case, the first expert is given the weight of 0.4 while the others were given the weight of 0.2 and the results were recorded. The same process is repeated for the other three experts. After the sensitivity analysis and comparison of the results, found that the findings are similar in each case with few exceptions. This shows the robustness of the results and how they are free from human bias. The results of cause-effect parameters and barriers ranking based through sensitivity analysis (Tables 12 and 13). A visual representation of cause-effect relation or net effect value based on sensitivity analysis is given in Figure 10.

<<<<<<<<<<<Insert Table 12 here>>>>>>>>>>

<<<<<<<<<<<Insert Table 13 here>>>>>>>>>>

<<<<<<<<<<<Insert Figure 10 here>>>>>>>>>>>

5.6 Theoretical Contributions

The study key contributions are as follows. First, this study identified the prominent factors that hinder the integration of LSS with I4.0. Second, this study analysed the causal relationship between 15 prominent factors. Third, research have prioritised the barriers so that managers can effectively understand priorities for resolving the barriers. The barriers analysis in the study using the Grey-DEMATEL, which is an MCDM approach. Although other MCDM techniques can also be used, Grey-DEMATEL has significant benefits over others i.e., it provides cause-effect relationships among the factors while accounting for inappropriate human judgments or errors. Finally, sensitivity analysis was performed to check the credibility of the results, eliminate bias in the results and reinforce scientific validity by assigning different weights to expert opinions and comparing the results with the original results. The key findings of this research are as follows:

1. Major barriers to the implementation of LSS with I4.0 in an Indian automotive components manufacturing industry were identified.
2. Interrelationships among the barriers and sub-barriers were analysed.
3. The grey-DEMATEL method has been developed to analyse the causal relationship among the barriers and sub-barriers.
4. Sensitivity analysis were conducted to show the robustness of the proposed method.
5. A case study from an Indian automotive component manufacturer was used to demonstrate the proposed framework.

This study contributes to the identification and unearthing of the relationships between barriers, that the organisation can control while implementing LSS with I4.0. The controlling of these resources can be valuable, rare non imitable, and nonsubstitutable resources & capabilities and can result in a competitive advantage for the firm (Kraaijenbrink *et al*., 2010). This article thus contributes to the identification of internal barriers within the firm and the relationships among them leading to its contribution to the resource-based theory.

5.7 Managerial Implications

The results of this study provide many implications for management. Integration of LSS with I4.0 helps to increase productivity and quality and reduces the idle time of resources. The research provides guidelines to managers and decision-makers with insight what are the barriers hindering the implementation of LSS with I4.0. As a result, the case organisation will be able to easily concentrate on its weak areas to overcome any barriers. As the present study is based on the integration of LSS with I4.0, therefore one of the major implications of this study is the ease with which different industries will be able to integrate both, LSS and I4.0. Furthermore, it will also help identify different barriers that affect their successful integration. It will provide a roadmap to managers and a strategic plan for the implementation of LSS with I4.0. Managers can use this work as a reference to identify which barriers have to be dealt with beforehand. Also, this can in identifying new barriers and conducting their analysis for the efficient integration of LSS with I4.0.

6 Conclusion, limitations, and directions for future research

The first research objective of this study was to identify the barriers that make integration of LSS and I4.0 difficult in the automobile Industry. Therefore, the barriers were identified through literature review and expert opinion. Further, barriers were analysed to identify the cause-effect relationships. Grey-DEMATEL approach is adopted to analyse the cause-effect relationships among these barriers. Among the identified 15 barriers in the study, 10 were found to be cause and five were effect barriers that were affected by cause barriers. This study highlights the impact of the barriers while implementing LSS in the integration of I4.0. Also, this study presents a way to prioritise the barriers and identify barriers to be resolved. The 'Lack of long-term vision', 'Timely and accurate data availability' and 'Lack of automation were the top three prominent barriers. This helps the management to understand that companies must be motivated toward implementing LSS with I4.0 to get fruitful results in the long term. Also, the industry should adopt modern technologies and know the importance of the availability of quality data since it can highly impact other barriers. Thus, this study will provide the necessary roadmap to the managers for the successful adoption of LSS with I4.0.

A seamless integration of LSS with I4.0 may be impeded by these barriers. To overcome these barriers, all stakeholders must be involved, training and education must be provided, technology must be upgraded, and the industry must have a supportive organisational culture. As per the discussion with the case organisation, now they have started giving training to all employees, conducting the cost-benefit analysis, and are ready to upgrade their technology by adopting software like MES/SCADA. By overcoming these barriers, the synergy between LSS and I4.0 can be increased, which in turn leads to better performance, improved quality, and a more efficient organisation. The research provides holistic perspective, mitigating risk of failure, synergy identification, and enhancing decision-making capabilities for implementation of LSS with I4.0.

The proposed framework is broad enough to be applied to any automotive manufacturing industry. Further, by modifing the input parameters (barriers) it can be applied to any other manufacturing industry. In order to adapt this framework to any other manufacturing industry, it is recommended that managers, researchers, and practitioners should consult with their domain experts to modify input parameters (barriers) to get industry-specific results.

Further, future research opportunities may also arise from the limitations of the study. 15 barriers were analysed in the study, and more than 15 barriers can also be used in further studies. The barriers were analysed based on the insights provided by four experts, while the views of more experts will be considered in future studies. The research was based on the automobile industry, but some other industrial sectors can also be taken into consideration. The MCDM techniques other than Grey-DEMATEL can be applied, and the outcomes can be compared with this study.

References:

Aggarwal, S., & Srivastava, M. K. (2019). A grey-based DEMATEL model for building collaborative resilience in supply chain. International Journal of Quality & Reliability Management, 36(8), 1409-1437.

Ali, S. M., Hossen, M. A., Mahtab, Z., Kabir, G., & Paul, S. K. (2020a). Barriers to lean six sigma implementation in the supply chain: An ISM model. Computers & Industrial Engineering, 149, 106843.

Ali, Y., Younus, A., Khan, A. U., & Pervez, H. (2020b). Impact of Lean, Six Sigma and environmental sustainability on the performance of SMEs. International Journal of Productivity and Performance Management 70(8), 2294-2318.

Alnadi, M., & McLaughlin, P. (2021). Critical success factors of Lean Six Sigma from leaders' perspective. International Journal of Lean Six Sigma 12(5) .

Ambekar, S., & Hudnurkar, M. (2017). Factorial structure for Six Sigma project barriers in Indian manufacturing and service industries. TQM Journal, 29(5), 744–759. https://doi.org/10.1108/TQM-02-2017-0021

Amjad, M. S., Rafique, M. Z., & Khan, M. A. (2021). Modern divulge in production optimization: an implementation framework of LARG manufacturing with I4.0. International Journal of Lean Six Sigma, 12(5), 992-1016.

Antony, J., Krishan, N., Cullen, D., & Kumar, M. (2012). Lean Six Sigma for higher education institutions (HEIs). International Journal of Productivity and Performance Management, 61(8), 940–948. https://doi.org/10.1108/17410401211277165

Anvari, F., Edwards, R., & Agung, H. (2020). Lean Six Sigma in smart factories based on Industry 4.0. *Int. J. Emerg. Trends Energy Environ.(IJETEE)*, *1*, 1-26, http://globalpublisher.org/ijetee-volume-1-issue-1/http://globalpublisher.org/journals-1002/www.globalpublisher.org

Bai, C., & Sarkis, J. (2013). A grey-based DEMATEL model for evaluating business process management critical success factors. *International Journal of Production Economics*, *146*(1), 281-292.

Belhadi, A., Touriki, F. E., & Fezazi, S. (2017). Prioritizing the solutions of lean implementation in SMEs to overcome its barriers: An integrated fuzzy AHP-TOPSIS approach. In Journal of Manufacturing Technology Management (Vol. 28, Issue 8, pp. 1115–1139). Emerald Group Publishing Ltd. https://doi.org/10.1108/JMTM-04-2017-0066

Bhasin, S. (2012). Prominent obstacles to lean. International Journal of Productivity and Performance Management, 61(4), 403–425. https://doi.org/10.1108/17410401211212661

Bhat, V. S., Bhat, S., & Gijo, E. V. (2020). Simulation-based lean six sigma for I4.0: an action research in the process industry. International Journal of Quality & Reliability Management, 38(5), 1215-1245.

Buer, S. V., Strandhagen, J. O., & Chan, F. T. (2018). The link between I4.0 and lean manufacturing: mapping current research and establishing a research agenda. *International journal of production research*, *56*(8), 2924-2940.

Chandra, M., Shahab, F., Vimal, K. E. K., & Rajak, S. (2022). Selection for additive manufacturing using hybrid MCDM technique considering sustainable concepts. *Rapid Prototyping Journal,* Vol. 28 No. 7, pp. 1297-1311. https://doi.org/10.1108/RPJ-06-2021-0155.

Chen, G., Wang, P., Feng, B., Li, Y., & Liu, D. (2020). The framework design of smart factory in discrete manufacturing industry based on cyber-physical system. *International Journal of Computer Integrated Manufacturing*, *33*(1), 79-101.

Chiarini, A., & Kumar, M. (2021). Lean Six Sigma and I4.0 integration for Operational Excellence: evidence from Italian manufacturing companies. Production Planning and Control, 32(13), 1084–1101. https://doi.org/10.1080/09537287.2020.1784485

Da Silva, V. L., Kovaleski, J. L., Pagani, R. N., Silva, J. D. M., & Corsi, A. (2020). Implementation of Industry 4.0 concept in companies: Empirical evidences. *International Journal of Computer Integrated Manufacturing*, *33*(4), 325-342.

Dwivedi, A., Shardeo, V. and Patil, A. (2021). Analysis of recovery measures for sustainable freight transportation, Journal of Asia Business Studies (In press)

Dyer, G.W. and Wilkins, A.L. (1991), "Better stories, not better constructs, to generate better theory: a rejoinder to Eisenhardt", Academy of Management Journal, Vol. 16 No. 3, pp. 613-619

Eisenhardt, K.M. (1989), “Building theories from case study research”, Academy of Management Review, Vol. 14 No. 4, pp. 532-550

Frank, A. G., Dalenogare, L. S., & Ayala, N. F. (2019). I4.0 technologies: Implementation patterns in manufacturing companies. International Journal of Production Economics, 210, 15–26. https://doi.org/10.1016/j.ijpe.2019.01.004

Gaikwad, S. K., Paul, A., Moktadir, M. A., Paul, S. K., & Chowdhury, P. (2020). Analyzing barriers and strategies for implementing Lean Six Sigma in the context of Indian SMEs. Benchmarking: An International Journal.

Gandhi, J., Thanki, S., & Thakkar, J. J. (2021). An investigation and implementation framework of Lean Green and Six Sigma (LG&SS) strategies for the manufacturing industry in India. The TQM Journal, 33(8), 1705-1734.

Ghobakhloo, M., & Fathi, M. (2019). Corporate survival in I4.0 era: the enabling role of lean-digitized manufacturing. Journal of Manufacturing Technology Management, 31(1), 1-30.

Gupta, A., Sharma, P., Jain, A., Xue, H., Malik, S. C., & Jha, P. C. (2019). An integrated DEMATEL Six Sigma hybrid framework for manufacturing process improvement. Annals of Operations Research. https://doi.org/10.1007/s10479-019-03341-9

Gutierrez-Gutierrez, L., de Leeuw, S., & Dubbers, R. (2016). Logistics services and Lean Six Sigma implementation: a case study. International Journal of Lean Six Sigma, 7(3), 324–342. https://doi.org/10.1108/IJLSS-05-2015-0019

Horváth, D., & Szabó, R. Z. (2019). Driving forces and barriers of I4.0: Do multinational and small and medium-sized companies have equal opportunities?. Technological forecasting and social change, 146, 119-132.

Jayaraman, K., Leam Kee, T., & Lin Soh, K. (2012). The perceptions and perspectives of Lean Six Sigma (LSS) practitioners. The TQM Journal, 24(5), 433–446. https://doi.org/10.1108/17542731211261584

Karadayi-Usta, S. (2020). An Interpretive Structural Analysis for I4.0 Adoption Challenges. IEEE Transactions on Engineering Management, 67(3), 973–978. https://doi.org/10.1109/TEM.2018.2890443

Ketokivi, M. and Choi, T. (2014), “Renaissance of case research as a scientific method”, Journal of Operations Management, Vol. 32 No. 5, pp. 232-240.

Khanzode, A. G., Sarma, P. R. S., & Goswami, M. (2021). Modelling interactions of select enablers of Lean Six-Sigma considering sustainability implications: an integrated circular economy and I4.0 perspective. *Production Planning & Control*, 1-17.

Kirkire, M. S., & Rane, S. B. (2017). Evaluation of success factors for medical device development using grey DEMATEL approach. Journal of Modelling in Management, 12(2), 204-223.

Kolberg, D., Knobloch, J., & Zühlke, D. (2017). Towards a lean automation interface for workstations. International Journal of Production Research, 55(10), 2845–2856. https://doi.org/10.1080/00207543.2016.1223384

Kumar, R., & Kumar, V. (2015). Lean manufacturing in Indian context: A survey. Management Science Letters, 5(4), 321–330. https://doi.org/10.5267/j.msl.2015.2.009

Kumar, S., Raut, R. D., Aktas, E., Narkhede, B. E., & Gedam, V. V. (2022). Barriers to adoption of industry 4.0 and sustainability: a case study with SMEs. *International Journal of Computer Integrated Manufacturing*, 1-21.

Letchumanan, L. T., Gholami, H., Yusof, N. M., Ngadiman, N. H. A. B., Salameh, A. A., Štreimikienė, D., & Cavallaro, F. (2022). Analyzing the Factors Enabling Green Lean Six Sigma Implementation in the I4.0 Era. *Sustainability*, *14*(6), 3450.

Li, S., Peng, G. C., & Xing, F. (2019). Barriers of embedding big data solutions in smart factories: insights from SAP consultants. *Industrial Management & Data Systems*.

Management, 16(2), 728–764. https://doi.org/10.1108/JM2-07-2019-0155

McCutcheon, D.M. and Meredith, J.R. (1993), "Conducting case study research in operations management", Journal of Operations Management, Vol. 11 No. 3, pp. 239-256

Meredith, J. (1998), "Building operations management theory through case and field research", Journal of Operations Management, Vol. 16 No. 4, pp. 441-454.

Moya, C. A., Galvez, D., Muller, L., & Camargo, M. (2019). A new framework to support Lean Six Sigma deployment in SMEs. International Journal of Lean Six Sigma, 10(1), 58–80. https://doi.org/10.1108/IJLSS-01-2018-0001

Mrugalska, B., & Wyrwicka, M. K. (2017). Towards Lean Production in I4.0. Procedia Engineering, 182, 466–473. https://doi.org/10.1016/j.proeng.2017.03.135

Narwane, V. S., Raut, R. D., Gardas, B. B., Narkhede, B. E., & Awasthi, A. (2022). Examining smart manufacturing challenges in the context of micro, small and medium enterprises. *International Journal of Computer Integrated Manufacturing*, *35*(12), 1395-1412.

Nimawat, D., & Gidwani, B. D. (2021). Identification of cause and effect relationships among barriers of I4.0 using decision-making trial and evaluation laboratory method. Benchmarking. https://doi.org/10.1108/BIJ-08-2020-0429

Nimawat, D., & Gidwani, B. D. (2021). Prioritization of barriers for Industry 4.0 adoption in the context of Indian manufacturing industries using AHP and ANP analysis. *International Journal of Computer Integrated Manufacturing*, *34*(11), 1139-1161.

Nordin, N., Md Deros, B., & Abd Wahab, D. (2010). A survey on lean manufacturing implementation in Malaysian automotive industry. International Journal of Innovation, Management and Technology, 1(4), 374–380.

Panetto, H., & Molina, A. (2008). Enterprise integration and interoperability in manufacturing systems: Trends and issues. Computers in Industry, 59(7), 641–646. https://doi.org/10.1016/j.compind.2007.12.010

Patel, A. S., & Patel, K. M. (2021). Critical review of literature on Lean Six Sigma methodology. International Journal of Lean Six Sigma, 12(3), 627-674.

Pereira, A. C., Dinis-Carvalho, J., Alves, A. C., & Arezes, P. (2019). How I4.0 can enhance lean practices. *FME Transactions*, *47*(4), 810-822.

Pongboonchai-Empl, T., Antony, J., Garza-Reyes, J. A., Komkowski, T., & Tortorella, G. L. (2023). Integration of Industry 4.0 technologies into Lean Six Sigma DMAIC: a systematic review. *Production Planning & Control*, 1-26.

Prakash, S., Kumar, S., Soni, G., Mahto, R. V., & Pandey, N. (2021). A decade of the international journal of lean six sigma: bibliometric overview. International Journal of Lean Six Sigma, 13(2), 295- 341.

Raj, A., Dwivedi, G., Sharma, A., Lopes de Sousa Jabbour, A. B., & Rajak, S. (2020). Barriers to the adoption of I4.0 technologies in the manufacturing sector: An inter-country comparative perspective. International Journal of Production Economics, 224. https://doi.org/10.1016/j.ijpe.2019.107546

Rajak, S., Parthiban, P., & Dhanalakshmi, R. (2021a). A DEA model for evaluation of efficiency and effectiveness of sustainable transportation systems: a supply chain perspective. *International Journal of Logistics Systems and Management*, *40*(2), 220-241.

Rajak, S., Parthiban, P., & Dhanalakshmi, R. (2021b). Analyzing barriers of sustainable transportation systems in India using Grey-DEMATEL approach: A supply chain perspective. International Journal of Sustainable Engineering, 14(3), 419-432.

Raji, I. O., Shevtshenko, E., Rossi, T., & Strozzi, F. (2021). I4.0 technologies as enablers of lean and agile supply chain strategies: an exploratory investigation. International Journal of Logistics Management. https://doi.org/10.1108/IJLM-04-2020-0157

Rathi, R., Singh, M., Kumar Verma, A., Singh Gurjar, R., Singh, A., & Samantha, B. (2021). Identification of Lean Six Sigma barriers in automobile part manufacturing industry. Materials Today: Proceedings. https://doi.org/10.1016/j.matpr.2021.05.221

Raval, S. J., & Kant, R. (2017). Study on Lean Six Sigma frameworks: a critical literature review. In International Journal of Lean Six Sigma (Vol. 8, Issue 3, pp. 275–334). Emerald Group Publishing Ltd. https://doi.org/10.1108/IJLSS-02-2016-0003

Raval, S. J., Kant, R., & Shankar, R. (2021). Analyzing the critical success factors influencing Lean Six Sigma implementation: fuzzy DEMATEL approach. Journal of Modelling in

Riley, B. W., Kovach, J. V., & Carden, L. (2013). Developing a policies and procedures manual for a consumer lending department: a design for Six Sigma case study. *Engineering Management Journal*, *25*(3), 3-15.

Ringen, G., & Holtskog, H. (2013). How enablers for lean product development motivate engineers. *International Journal of Computer Integrated Manufacturing*, *26*(12), 1117-1127.

Saxby, R., Cano-Kourouklis, M., & Viza, E. (2020). An initial assessment of Lean Management methods for I4.0. TQM Journal, 32(4), 587–601. https://doi.org/10.1108/TQM-12-2019-0298.

Shirey, W. T., Sullivan, K. T., Lines, B., & Smithwick, J. (2017). Application of Lean Six Sigma to Improve Service in Healthcare Facilities Management: A Case Study. Journal of Facility Management Education and Research, 1(1), 9–18. https://doi.org/10.22361/jfmer/78724

Shukla, V., Swarnakar, V., & Singh, A. R. (2021). Prioritization of lean six sigma project selection criteria using the best-worst method. Materials Today: Proceedings, 47, 5749-5754.

Si, S. L., You, X. Y., Liu, H. C., & Zhang, P. (2018). DEMATEL Technique: A Systematic Review of the State-of-the-Art Literature on Methodologies and Applications. In Mathematical Problems in Engineering (Vol. 2018). Hindawi Limited. https://doi.org/10.1155/2018/3696457

Siggelkow, N. (2007), "Persuasion with case studies", Academy of Management Journal, Vol. 50 No. 1, pp. 20-24.

Singh, M., Kumar, P., & Rathi, R. (2019). Modelling the barriers of Lean Six Sigma for Indian micro-small medium enterprises: An ISM and MICMAC approach. TQM Journal, 31(5), 673–695. https://doi.org/10.1108/TQM-12-2018-0205

Sony, M. (2020). Design of cyber physical system architecture for I4.0 through lean six sigma: conceptual foundations and research issues. Production & Manufacturing Research, 8(1), 158-181.

Sreedharan V, R., & Sunder M, V. (2018). A novel approach to lean six sigma project management: a conceptual framework and empirical application. Production Planning & Control, 29(11), 895-907.

Sreedharan V, R., Nair, S., Chakraborty, A., & Antony, J. (2018). Assessment of critical failure factors (CFFs) of Lean Six Sigma in real-life scenario: evidence from manufacturing and service industries. Benchmarking: An International Journal, 25(8), 3320-3336.

Swarnakar, V. and Vinodh, S. (2016), "Deploying Lean Six Sigma framework in an automotive component manufacturing organization", International Journal of Lean Six Sigma, Vol. 7 No. 3, pp. 267-293.Swarnakar, V., Singh, A. R., Antony, J., Tiwari, A. K., & Cudney, E. (2021). Development of a conceptual method for sustainability assessment in manufacturing. Computers & Industrial Engineering, 158, 107403.

Tieng, K., Jeenanunta, C., Chea, P., & Rittippant, N. (2022). Roles of customers in upgrading manufacturing firm technological capabilities toward I4.0. *Engineering Management Journal*, *34*(2), 329-340.

Tseng, M. L. (2009). A causal and effect decision making model of service quality expectation using grey-fuzzy DEMATEL approach. Expert Systems with Applications, 36(4), 7738–7748. https://doi.org/10.1016/j.eswa.2008.09.011

Vigneshvaran, R., & Vinodh, S (2020). Development of a structural model based on ISM for analysis of barriers to integration of leanwith I4.0. TQM Journal. https://doi.org/10.1108/TQM-07-2020-0151

Vinodh, S., & Swarnakar, V. (2015). Lean Six Sigma project selection using hybrid approach based on fuzzy DEMATEL–ANP–TOPSIS. *International Journal of Lean Six Sigma*, 6(*4*), 313–338..

Voss, C., Tsikriktsis, N. and Frohlich, M. (2002), "Case research in operations management", International Journal of Operations and Production Management, Vol. 22 No. 2, pp. 195-219.

Xia, X., Govindan, K., & Zhu, Q. (2015). Analyzing internal barriers for automotive parts remanufacturers in China using grey-DEMATEL approach. Journal of Cleaner Production, 87(1), 811–825. https://doi.org/10.1016/j.jclepro.2014.09.044

Xing, F., Peng, G., Wang, J., & Li, D. (2022). Critical Obstacles Affecting Adoption of Industrial Big Data Solutions in Smart Factories: An Empirical Study in China. *Journal of Global Information Management (JGIM)*, *30*(1), 1-21.

Yadav, G., & Desai, T. N. (2016). Lean Six Sigma: a categorized review of the literature. *International Journal of Lean Six Sigma*, *7*(1), 2-24.

Yadav, G., & Desai, T. N. (2017). A fuzzy AHP approach to prioritize the barriers of integrated Lean Six Sigma. International Journal of Quality and Reliability Management, 34(8), 1167–1185. https://doi.org/10.1108/IJQRM-01-2016-0010.

Yadav, G., & Desai, T. N. (2017). Analyzing lean six sigma enablers: a hybrid ISM-fuzzy MICMAC approach. *The TQM Journal*, *29*(3), 488-511.

Yadav, G., Kumar, A., Luthra, S., Garza-Reyes, J. A., Kumar, V., & Batista, L. (2020a). A framework to achieve sustainability in manufacturing organisations of developing economies using industry 4.0 technologies' enablers. *Computers in industry*, *122*, 103280.

Yadav, G., Luthra, S., Huisingh, D., Mangla, S. K., Narkhede, B. E., & Liu, Y. (2020b). Development of a lean manufacturing framework to enhance its adoption within manufacturing companies in developing economies. *Journal of Cleaner Production*, *245*, 118726.

Yadav, N., Shankar, R., & Singh, S. P. (2020). Impact of Industry4. 0/ICTs, Lean Six Sigma and quality management systems on organisational performance. The TQM Journal, 32(4), 815-835.

Yadav, N., Shankar, R., & Singh, S. P. (2021). Hierarchy of Critical Success Factors (CSF) for Lean Six Sigma (LSS) in Quality 4.0. International Journal of Global Business and Competitiveness, 16(1), 1–14. https://doi.org/10.1007/s42943-020-00018-0

Yang, Y., & John, R. (2003). Grey systems and interval valued fuzzy sets Computing with words in Fuzzy Cognitive Maps View project Multi-fuzzy sets View project Grey Systems and Interval Valued Fuzzy Sets. https://www.researchgate.net/publication/221399098

Yin, R.K. (2014), Case Study Research: Design and Methods, Sage, Thousand Oaks, CA.

Zhang, L., Narkhede, B. E., & Chaple, A. P. (2017). Evaluating lean manufacturing barriers: An interpretive process. Journal of Manufacturing Technology Management, 28(8), 1086–1114. https://doi.org/10.1108/JMTM-04-2017-0071

Zhu, X. Y., Zhang, H., & Jiang, Z. G. (2020). Application of green-modified value stream mapping to integrate and implement lean and green practices: A case study. *International Journal of Computer Integrated Manufacturing*, *33*(7), 716-731.