Benchmarking: An International Journal

Empirical assessment of the causal relationships among lean criteria using DEMATEL method

Vikram Sharma Amit Rai Dixit Mohammad Asim Qadri

Received 21 August 2014
Revised 8 December 2014
Accepted 29 December 2014

Empirical assessment of the causal relationships among lean criteria using DEMATEL method

Vikram Sharma
Department of Mechanical Engineering, Galgotias College of Engineering and Technology, Noida, India
Amit Rai Dixit
Department of Mechanical Engineering, Indian School of Mines, Dhanbad, India, and
Mohammad Asim Qadri
Department of Mechanical Engineering, Galgotias College of Engineering and Technology, Noida, India

Abstract

Purpose – It is difficult for anyone to implement all the lean tools simultaneously. One of the core issues is identifying critical criteria for the successful implementation of lean manufacturing (LM) and evaluating them. The purpose of this paper is to analyze the causal relationships of LM criteria in a machine tool manufacturing firm located in national capital region of India using the Decision-Making Trial and Evaluation Laboratory (DEMATEL) method.
Design/methodology/approach – The research paper presents a blend of theoretical framework and practical applications. Based on literature review, 17 LM criteria were extracted that were validated by experts. A questionnaire was developed that was answered by experts serving in the XYZ machine tool manufacturing firm. Then, the DEMATEL method was applied to analyze the importance of criteria and the casual relations among the criteria were developed.
Findings – Using DEMATEL, the lean criteria were divided into cause group and effect group. In this study, information technology, computer-integrated manufacturing, enterprise resource planning, training, fixed position layout, smart processes and automation and concurrent engineering were classified in the cause group. Just in time, value stream mapping, 5-S, single minute exchange of die, visual control, job scheduling, standardized work, cellular manufacturing, poka-yoke, and total quality management were categorized in the effect group. The DEMATEL framework indicates that "training" is the most influencing factor for the lean implementation process in machine tool sector.
Originality/value – To know the key lean criteria and relationship among them can help many organizations to develop lean competencies. If the authors want to obtain high performance in terms of the effect group factors, it would be necessary to control and pay a great deal of attention to the cause group factors beforehand. This study is perhaps among the first few with focus on segmenting the set of lean criteria into some meaningful portions in order to effectively facilitate its implementation. The paper provides useful insights to the lean production implementers, consultants, and researchers.

Keywords India, DEMATEL, Lean production, Lean manufacturing, Production management, Machine tool firms
Paper type Case study

Benchmarking: An International Journal
Vol. 23 No. 7, 2016
pp. 1834-1859

1463-5771
DOI 10.1108/BIJ-08-2014-0078

Authors express gratitude to the experts from XYZ machine tool manufacturing firm whose valuable inputs helped in understanding contextual relationship between the lean criteria used in this study.

1. Introduction

Today's acute business competition compels firms to rapidly innovate and improve resulting in a continuous search for techniques that can reduce cost, and improve quality, productivity and operational performance. Lean manufacturing (LM) has been the buzzword in the area of manufacturing for past few years (Singh *et al.*, 2010). Under the lean lens, all non-value adding activities are regarded as some form of waste that divert resources from the value adding activities. According to the lean enterprise institute, founded by James P. Womack in 1997, lean means creating more value for customers with fewer resources. Lean production is a hybrid of both mass and craft production systems (Genaidy and Karwowski, 2003). It aims for waste removal both inside and between companies (Hines and Taylor, 2000). A LM philosophy requires respect for people, continuous improvement, a long-term view, a level of patience, a focus on process, and ability to understand where the individual is in his or her development (Ahmad and Azuan, 2013). The goal of lean manufacturing system (LMS) is doing more with less of time, space, human effort while giving the customer what they want in a highly economical manner (Paranitharan *et al.*, 2011).

Several benefits have been associated with LM implementation. Sánchez and Pérez (2001) indicate that lean production program in a shop, factory or company has the potential to increase productivity, reduce lead time and costs, and improve quality. After comparison of the current and future state of shop floor of the selected industry, Singh *et al.* (2010) found that reduction in lead time was 83.14 percent, reduction in processing time was 12.62 percent, reduction in work-in-process (WIP) inventory was 89.47 percent, and reduction in manpower requirement was 30 percent. The rise in productivity per operator was 42.86 percent. Dunstan *et al.* (2006) examined the application of LM in a mining environment. They described the implementation of certain LM elements that are applicable in such organizations and noted that health and safety-related incidents were reduced from 154 to 67; absenteeism was reduced by 3.4-1.8 percent, while about $2 million (Australian) were saved during the year 2006. Singh and Sharma (2009) showed that value stream mapping (VSM) is a versatile tool for lean implementation by means of a case study of an Indian manufacturing industry and witnessed 92.58 percent reduction in lead time, 2.17 percent reduction in processing time, 97.1 percent reduction in WIP and 26.08 percent reduction in manpower requirement.

While in recent years, many organizations both in India and abroad are implementing the principles and concepts of LM (Womack and Jones, 2003; Pavnaskar *et al.*, 2003; Shah and Ward, 2007) with the intention of achieving superior competitive advantage, few have managed to attain their objectives (Gurumurthy and Kodali, 2011). For instance, Kallange (2006) studied lean implementation failures and found that lean implementation failure rate is over 50 percent. Bamber and Dale (2000) found that there are two main stumbling blocks to the LM application in traditional aerospace manufacturing: the redundancy program and a lack of employee education in the concept and principles of lean production. Braglia *et al.* (2006) points out in his article that VSM, a commonly used lean implementation technique is basically a paper-and-pencil-based technique, so, the accuracy level is limited. The researchers further conclude that the number of versions that can be handled is low; in real situations, many companies are of a "high variety-low volume type," this requires many value streams and cannot be addressed by simple VSM. Balle (2005) in his report "Lean attitude" mentions that many failures in the attempts to implement lean occur due to fundamental misunderstanding of how to acquire lean. Raveendra (n.d.) in his case study "Failure factors in lean implementation" reports that a company based in Sri Lanka, having more than 7,000 employees hired consultants in an attempt to implement lean concept with the aim to improve efficiency but failed to gain any significant advantage. The study of failed cases of implementing lean highlights the need to develop new frameworks that facilitate successful implementation of the concept. A common dilemma faced during lean implementation is the identification of decisive criteria of lean production and evaluating them. The goal of this research is to analyze the causal relationships of lean production criteria in a machine tool manufacturing firm located in national capital region of India.

Toward this goal, Decision-Making Trial and Evaluation Laboratory (DEMATEL) approach is employed since it is a powerful technique in causal analysis that enables the researchers to separate the involving criteria of a system into the cause and effect groups (Lin and Wu, 2008). This technique allows the decision makers to acknowledge the criteria of greater influence. DEMATEL has been successfully applied to many research fields with the purpose to render sophisticated problems and transform complex systems into structurally causal and effect relationships (Lin *et al.*, 2011). Therefore, in this research, we use DEMATEL for analyzing the lean implementation criteria in machine tool firms.

There are many criteria suggested by researchers and practitioners for lean implementation but how should these criteria be implemented is still not very clear (Kajdan, 2008). This impending question needs to be addressed. The criteria for lean implementation not only affect the key performance indicators of the business but they also influence one another making it imperative to understand the mutual relationships among these lean criteria. The identification of the lean criteria that are at the root of some other criteria and those which are most influenced by the others would be helpful for the top management in implementing the lean programs. This can work as a guide for taking appropriate action in implementing lean programs (Sharma *et al.*, 2015).

The remainder of this paper is organized as follows. Section 2 provides a literature review of LMSs and the key criteria for lean implementation. The DEMATEL methodology and model development are covered in Section 3. The last section deals with results and discussions. Acronyms used with their meanings is given in Glossary, while the steps involved in DEMATEL methodology are given in Appendix.

2. Literature review

Manufacturing leanness is a strategy to incur less input to better achieve the organization's goals through producing better output (Bayou and De Korvin, 2008). Many case studies exist that deal with the LM implementation in a wide variety of industrial sectors other than manufacturing. For instance, Petersen (2012) developed lean indicators to detect waste in software maintenance. Dave (2013) developed a construction management system based on lean construction and building information modeling. Though lean initiatives are undertaken in other sectors, the number of LM implementations in the manufacturing sector is much higher as compared to other sectors. Hence, this review focusses only on LM implementations in manufacturing sector. Table I provides a list of case studies describing the LM implementation in manufacturing sector. A cursory review of these papers will reveal that LMS have been established in different manufacturing systems such as aerospace (job shop type), machine tools (batch production type), automobile (mass production type) and process industry.

Industry type	Researchers	Conclusion
Aerospace	Oppenheim *et al.* (2011)	Answers to the fundamental questions of how the competitiveness of the aerospace and other industrial sectors can be strengthened using lean enablers
	McManus *et al.* (2007)	Lean engineering framework for aeronautical
	Crute *et al.* (2003)	Understanding the challenges to implementing lean in aerospace
	Michaels (1999)	Study a lean aerospace supply chain
	Slack (1998)	Study the application of lean principles to the military aerospace product development process
	Haque and Moore (2004)	Measuring performance for lean product introduction in the aerospace industry
	James-Moore and Gibbons (1997)	Study extent of lean implementation in civil aerospace companies
	Mathaisel (2005)	Present a lean architecture for transforming the aerospace maintenance, repair and overhaul enterprise
	Hallam and Keating (2014)	A self-assessment of lean enterprise maturity
	Winter *et al.* (2013)	The application of a lean philosophy during manufacture of advanced airframe structures in a new product introduction (NPI) environment
	Martínez-Jurado and Moyano-Fuentes (2014)	Key determinants of lean production adoption
	Wang *et al.* (2012)	Implementation of lean model for carrying out value stream mapping in the aerospace engine case production
Automobile	Liang and Wang (2013)	Study the development strategy of lean logistics for automobile enterprises
	Imam and Sudipto Sarkar (2012)	Lean Sigma a road to success: a perspective of the Indian automobile industry. *Global Journal of Researches in Engineering*, Vol. 12 No. 1-A
	Hasle (2014)	Evaluation the possibilities for an employee supportive lean practices
	Mohanty *et al.* (2007)	Describe some learning from the literature and actual lean practices in USA, UK, and India
	Herron and Hicks (2008)	Study the transfer of selected LM techniques from Japanese automotive manufacturing into general manufacturing (UK)
	Bayou and De Korvin (2008)	Measure the leanness of manufacturing systems at Ford Motor Company and General Motors
	Vinodh *et al.* (2011)	Study the implementation of lean sigma framework in an Indian automotive valves manufacturing organization
	Belokar *et al.* (2012)	Study application of value stream mapping in automobile industry using a case study
Electronics	Doolen and Hacker (2005)	Assess the implementation of lean practices within an organization using a survey
	Wong and Wong (2011)	Study the approaches and practices of LM in electrical and electronics companies
	Jeyaraman and Teo (2010)	Present a conceptual framework for critical success factors of lean six sigma
Process industry	Melton (2005)	Analyze benefits of LM to the process industries
Machine tools	Eswaramoorthi *et al.* (2011)	Present results of a survey on lean practices in Indian machine tool industries

Table I. Summary of industries in which LM practices have been studied

LM was initiated within the automotive sector. However, since the publication of the influential book, *The Machine That Changed the World*, there has been a range of documented cases of lean implementation in a variety of sectors. Oppenheim *et al.* (2011) extol that lean thinking has been successfully applied in various work fields such as general manufacturing, aerospace, healthcare, and service industries. Electronic manufacturers too have implemented a broad range of lean practices (Doolen and Hacker, 2005). There is an emerging field of lean systems engineering, that is, the application of lean principles, practices, and tools to the related aspects of enterprise management in order to enhance the delivery of value. In India, the automobile industry has been in the forefront of lean adoption as compared to machine tool industry. This is largely due to the fact that automobile industries have shown professional approach may be due to a large number of foreign collaborations and having witnessed a major quality revolution. On the other hand, the machine tool industry in India is still to mature primarily due to lax government policies, shortage of funds and inadequate research and development.

Some researchers suggest that, the VSM can serve as a good starting point for any enterprise that wants to be lean (Belokar *et al.*, 2012). People in the organization should possess the lean mindset and act in the lean way in order to make a lean initiative successful (Wong and Wong, 2011). Lean has been praised for empowering employees, and it has been criticized for intensifying work and impairing the health and well-being of employees (Hasle, 2014). Migrating lean to engineering processes such as product development is ongoing in the industry as the cost and value of products is determined primarily in the product development stage (McManus *et al.*, 2007). Efforts have also been directed by certain original equipment manufacturers in automobile and aerospace industry to implement lean throughout the supply chains.

Study by Hallam and Keating (2014) in US and UK industry investigates the use of lean enterprise self-assessment utilizing the Lean Enterprise Self-Assessment Tool (LESAT) developed by Massachusetts Institute of Technology and University of Warwick, as a means for measuring their current state of leanness in leadership/transformation processes, life-cycle processes, and enabling infrastructure. The study reveals that a clear opportunity related to lean enterprise transformation exists in raising the maturity of these enterprises in understanding their current value streams and defining their future value streams. The leanness measure should utilize the fuzzy-logic methodology since lean is a matter of degree (Bayou and De Korvin, 2008). There are series of factors that can affect the success of lean adoption decision, such as a deep-rooted culture of total quality, the role of top management, a lean organizational structure, the lean leader role and institutional support (Martínez-Jurado and Moyano-Fuentes, 2014).

Few researchers have analyzed lean implementation in SMEs (Von Axelson, 2009; Achanga *et al.*, 2006; Kumar *et al.*, 2006; Panizzolo *et al.*, 2012; Sharma *et al.*, 2011). A research by April *et al.* (2010) brings out that SMEs find it difficult to implement productivity improvement tools, particularly those associated with LM. Also, SMEs suffer from scarcity of resources as compared to the larger companies that have more success due to greater access to resources. Still, SMEs can deploy soft technologies such as lean and six sigma for achieving dramatic results in cost, quality and time by focussing on process performance (Kumar *et al.*, 2006). Leadership, management, finance organizational culture and skills and expertise, among other factors; are classified as the most pertinent issues critical for the successful adoption of LM within SMEs environment (Achanga *et al.*, 2006). Forza (1996) explores the differences between the traditional and the lean production plants and concludes that lean production plants use more teams for problem solving, take employees' suggestions more seriously, rely more heavily on quality feedback both from workers and supervisors, document production procedures more carefully and have employees able to perform a greater variety of tasks including statistical process control. In Indian SMEs, applications of advanced manufacturing strategies have been far fewer (Sharma *et al.*, 2011). To provide with a way to implement lean effectively, this research proposes a DEMATEL-based methodology for SMEs.

A literature review followed by a brainstorming session was carried out with experts from XYZ machine tools firm to finalize the 17 criteria for lean production implementation as given in Table II:

(1) Pull system or just in time (JIT): according to a research by Phan and Matsui (2010) high-performance plants highly focus on JIT that is a system where the production or movement of inventory items is initiated as required by the using department or the customer. JIT is applied to that portion of the supply chain where demand uncertainty is high. The basic feature is that production and distribution are demand driven, zero inventory or minimum inventory is maintained and, response is made to specific orders. Inventory management strategies such as JIT can be aided by using RFID as an electronic kanban, triggering the pull-based use of material (Brintrup *et al.*, 2010).

S. no.	Lean manufacturing practice	Type of waste removed	Authors
1	Pull system (JIT)	Over production, unnecessary inventory	Brintrup *et al* (2010), Phan and Matsui (2010)
2	Value stream mapping	Over production, unnecessary inventory	Bhamu *et al.* (2012), Mohanraj *et al.* (2011), Kuhlang *et al.* (2013)
3	Information technology	Over production, transportation, unnecessary motion	Cottyn *et al.* (2011)
4	5-S	Delay	Devadasan *et al.* (2012)
5	Single minute exchange of die	Delay	McIntosh *et al.* (2000), Carrizo and Campos (2011), Shingo (1985)
6	Visual control	Delay	Parry and Turner (2006)
7	Computer-integrated manufacturing	Delay, transportation	Groover (2011), Scheer (2012)
8	Enterprise resource planning	Underutilization of people	Mandal and El-Houbi (2009), Leon (2008)
9	Job scheduling	Underutilization of people	Devadasan *et al.* (2012)
10	Standardized work	Underutilization of people and undue motion	Devadasan *et al.* (2012)
11	Training	Underutilization of facilities	Devadasan *et al.* (2012)
12	Fixed position layout	Transportation	Devadasan *et al.* (2012)
13	Cellular manufacturing	Transportation	Kalpakjian and Schmid (2009), Dixit and Mishra (2008)
14	Poka-yoke	Processing wastes, defective parts	Shingo-Shingo
15	Smart processes and automation	Processing wastes, defective parts	Devadasan *et al.* (2012)
16	Total quality management	Processing wastes, defective parts	Karthi *et al.* (2011), Michael *et al.* (2010), Lee and Chang (2010)
17	Concurrent engineering	Delay	Pullan *et al.* (2011)

Table II.
LM criteria and types of waste removed

(2) VSM: a value stream comprises of all the actions, both value added and non-value added, currently required to complete a product or service from beginning to end. Thus, VSM visually represents what is going on in the supply chain. Improving processes is a common challenge for most enterprises (Kuhlang *et al.*, 2013). VSM helps to see and understand, document, analyze and improve the flow of material and information and improve quality as a product or service makes its way through the value stream (Mohanraj *et al.*, 2011; Bhamu *et al.*, 2012).

(3) Information technology (IT): IT deals with the use of computers and telecommunications for storing retrieving or transmitting information in business management. Cottyn *et al.* (2011) claim that IT and lean are interdependent and complementary. Using IT, the task of managing inventory has become easier. IT can also be utilized for eliminating unnecessary motions.

(4) 5-S: the 5-S program is a key component of a visual workplace, Kaizen (a system of continual improvement) and in-turn the LM. The 5-S program focusses to systematically achieve total organization, visual order, cleanliness and standardization. A well-organized workplace results in a safer, more efficient, and more productive operation. LM advocates adoption of 5-S for eliminating delays by maintaining good housekeeping facility as it helps in choosing the right tool without delay (Devadasan *et al.*, 2012).

(5) Single minute exchange of die (SMED): SMED refers to theory and techniques for performing setup operations in under ten minutes, that is, in a number of minutes expressed in a single digit (Shingo, 1985). It enables an organization to quickly convert a machine or process to produce a different product type. Set up time can become a big problem in manufacturing when a cutting tool, jig-fixture or a press needs to be set up for the production of another part. By applying the SMED method the set up times were reduced to a few minutes or even seconds in many cases thus improving productivity (Carrizo and Campos, 2011). It also avoids delay in loading work-piece on the machine or any other facilities. For instance, using SMED principles, the task of setting up jobs are carried out away from the machine or the facility. Thus, job can be loaded without any delay for carrying out machining operation (Devadasan *et al.*, 2012). McIntosh *et al.* (2000) emphasized on need to have certain design changes to the existing manufacturing system along with SMED implementation.

(6) Visual control: according to Parry and Turner (2006), visual control forms an important part of the communication process which drives lean factories. This is a technique employed in many places and contexts whereby control of an activity or process needs to be made easier or more effective by deliberate use of visual signals. For instance, progress indicators and problem indicators help assemblers see when production is ahead, behind or on schedule. They allow everyone to instantly see the group's performance.

(7) Computer-integrated manufacturing (CIM): CIM denotes the pervasive use of computer systems to design the products, plan the production, control the operations, and perform various information processing functions needed in a manufacturing firm (Groover, 2011). This integration allows individual processes to exchange information with each other and initiate actions. Computer systems communicate over a network. Typically, CIM systems link management functions with engineering, manufacturing, and support operations. It combines separate

applications, such as computer aided design, computer aided engineering, computer aided manufacturing, robotics, and manufacturing resource planning. Scheer (2012) considers that the essential objective of CIM is to streamline the manufacturing processes and to integrate them with other business functions (such as accounting, financing, distributing, marketing).

(8) Enterprise resource planning (ERP): ERP is an enterprise wide software solution that integrates and automates business functions of an organization such as finance/accounting, manufacturing, sales and service, customer and relationship management (Leon, 2008). ERP system aims to facilitate the flow of information between all business functions inside the boundaries of the organization and manage the connections to outside stakeholders. An ERP system has been the prime enforcer of best practices in many organizations (Mandal and El-Houbi, 2009).

(9) Job scheduling: job scheduling is used to avoid underutilization of people. If the jobs are scheduled, there is no ambiguity in carrying out activities at the workplace (Devadasan *et al.*, 2012).

(10) Standardized work: using standardized work technique, standardized work sheet is prepared to indicate the route and schedule of the jobs. The employees referring to standardized worksheets become knowledgeable in accomplishing their jobs successfully. Thus, waste resulting from underutilization of people can be reduced or eliminated (Devadasan *et al.*, 2012).

(11) Training: an important task that can be used to minimize underutilization of facility is to impart right training to the employees working on the facility. This is especially essential in case a new and advanced facility is installed. Employees should be further encouraged to make use of the skills and knowledge acquired during the training program while using the facility (Devadasan *et al.*, 2012).

(12) Fixed position layout: ideally, to manufacture a product, all the processes should be carried out at one location. For instance, if an aircraft has to be built, all the processes should be carried out at one location, components should be assembled at one location, and finally the complete assembly should be tested at the same location. This kind of processing and development of product at one location can be achieved in fixed position layout and it significantly reduces the transportation cost (Devadasan *et al.*, 2012).

(13) Cellular manufacturing (CM): CM is a method of producing similar products using cells, or groups of team members, workstations, or equipment, to facilitate operations by eliminating setup and unneeded costs between operations. Cells might be designed for a specific process, part, or a complete product (Dixit and Mishra, 2008). A cell is a group of workstations, machine tools, or equipment arranged to create a smooth flow so families of parts can be processed progressively from one workstation to another without waiting for a batch to be completed or requiring additional handling between operations (Arora *et al.*, 2013). Automated inspection and testing equipment can also be a part of such a cell. Central to these activities is a material handling system for transferring materials and parts among workstations (Kalpakjian and Schmid, 2009).

(14) Poka-yoke: poka-yoke is the Japanese term for mistake proofing proposed by Shingo-Shingo. A poka-yoke device is any mechanism that either prevents a

mistake from being made or makes the mistake obvious at a glance. The ability to find mistakes at a glance is essential because the causes of defects lie in worker errors, and defects are the results of neglecting those errors (Sharma *et al.*, 2015). Mistakes will not turn into defects if man made errors are discovered and eliminated beforehand.

(15) Smart process and automation: smart processes involving least stages and minimum time needed to avoid processing waste. IT can also be exploited so that electronic information can be quickly transmitted and the process is automated (Devadasan *et al.*, 2012).

(16) Total quality management (TQM): TQM is a comprehensive and structured approach to organizational management that seeks to improve the quality of products and services through ongoing refinements in response to continuous feedback. TQM is based on quality management from the customer's point of view (Sahay *et al.*, 2011). Researchers have tried to integrate LM and six sigma concept under the title "lean six sigma" (Karthi *et al.* 2011; Michael *et al.*, 2010). The six sigma systems can promote the enterprise competitive ability, such as pursuing cost improvement, promoting quality, the customer's satisfaction and valid strategy performance (Lee and Chang, 2010).

(17) Concurrent engineering (CE): CE is a product and process design methodology that includes simultaneous participation by engineering, operations, accounting, planning, customers, vendors and other functions, so that the input of all concerned parties are heard from during a project's conception, design and planning (Sharma *et al.*, 2008). Suggestion of various parties should be incorporated in design stage itself in order to prevent problems at later stages. Lean and concurrent engineering are widely acknowledged business process improvement strategies (Pullan *et al.*, 2011). These strategies can improve processes, reduce costs, and cut waste enabling organizations to remain competitive. Many companies still face enormous challenges when implementing and managing CE practices. This is due to the increased complexity of engineering products and processes, on one hand, and the lack of corresponding CE models and tools, on the other hand (Yassine and Braha, 2003).

3. Empirical case study

As discussed earlier, the criteria for lean implementation not only affect the key performance indicators of the business but they also influence one another. The empirical case study was undertaken with an objective to identify the cause group and the effect group among the lean criteria for a CNC machine tools manufacturing firm.

About the case firm XYZ

The case company, XYZ is a prominent Indian CNC machine tools manufacturing firm with more than 850 crores turnover and over 400 employees employs including workers, supervisors, engineers and top management. The company is one of the world's leading manufacturers CNC cylindrical grinding machines, turning machines, horizontal and vertical machining centers and the special purpose machines. Due to the worldwide challenge posed by the trend toward shorter product cycles and demanding customers, company XYZ requires performing with shorter lead time, higher quality, competitive prices, and improved customer service in a global context.

Though a number of theoretical and empirical studies address the impact of performance improvement methodologies in India industry, literature investigating the lean criteria for machine tool industry is limited. Formal models for analyzing criteria for implementing lean in Indian machine tool industry are virtually non-existent. Under the pressure of the fierce global competition, company XYZ wished to implement lean production practices by using the 17 lean criteria. However, those 17 lean criteria are difficult to execute at the same time, but are better suited to promote in a stepwise manner. Also, company XYZ encountered the problems concerning how to segment those 17 lean criteria into meaningful portions and how to utilize judgments of experts. For effective implementation of lean concept, organizations need to determine how they should enforce the criteria. The relationships among these criteria are also important for basic understanding of how to use the criteria. In order to acquire sensible subdivisions among lean criteria, company XYZ adopted our proposal and set up an expert committee comprising of the general manager, works manager, and engineers. The following section shows how company XYZ utilized our proposed DEMATEL method to evaluate and segment the 17 lean criteria for successful lean implementation.

Extensive review of extant literature was conducted to identify the criteria for lean implementation in manufacturing sector. A brainstorming session was carried out with five experts from machine tool sector to finalize the criteria for lean production implementation suitable for Indian manufacturing scenario. The experts have at least eight years experience and work in management positions in well-known Indian ISO certified machine tool manufacturing firms. They were informed about the objectives of the research. In the brainstorming session, managers were provided a comprehensive list of lean criteria out of which they were asked to select the most relevant criteria for Indian machine tools industry. After obtaining the 17 criteria for lean implementation from brainstorming session, a questionnaire was designed. A group of qualified experts reviewed and tested the designed questionnaire to assure the content validity of questionnaire. The group of qualified experts consisted of two professionals from academic institutions and one from industrial sector. After interviewing, the questionnaire was revised based on the experts' opinions. Now, the five experts from the case machine tool firm XYZ were asked to complete the questionnaire. After obtaining the completed questionnaires from the experts, DEMATEL analytical technique was used to determine the nature of contextual relationship. The 17 lean criteria for manufacturing sector and the results of DEMATEL analyses are given in the following sections.

DEMATEL methodology and its application at XYZ firm

Facing global competition, companies need to adopt LM strategies in order to maximize profits. In this section, an empirical study shows how a CNC machine tool manufacturing company applied our proposed DEMATEL method to segment the 17 LM criteria for promoting lean implementation successfully.

DEMATEL method was originally developed by the Science and Human Affairs Program of the Battelle Memorial Institute of Geneva between 1972 and 1976 that was intended to study and resolve the complicated and intertwined problem group (Tzeng *et al.*, 2007; Wu, 2008). The DEMATEL method was developed initially to study the structural relations in a complex system (Liou *et al.* 2007; Wu, 2008). The mathematical concepts evolved further and adapted in many academic fields, such as competence evaluation, industrial strategy analysis, solution analysis, and selection, etc. Wu and Lee (2007) combined DEMATEL and fuzzy theory to categorize the required competencies for better promoting the competency development of global managers. Further researches have reaffirmed the benefits of using DEMATEL method. Tseng (2009b) exploited this method in dealing with real estate agent service quality expectation ranking with uncertainty. Tsai and Chou (2009) employed DEMATEL to establish a selection model for evaluating the management systems for sustainable development in small and medium enterprises. This method can improve understanding of the specific problematique, the cluster of intertwined problems, and contribute to identification of workable solutions by a hierarchical structure (Hsu *et al.*, 2007; Tsai and Chou, 2009; Li and Tzeng, 2009; Shieh *et al.*, 2010). Unlike the traditional techniques such as analytic hierarchy process with the assumption that elements are independent (Wu and Tsai, 2011), this method, one of the structural modeling techniques, can identify the interdependence among the elements of a system through a causal diagram using digraphs to portray the basic concept of contextual relationships and the strengths of influence among the elements (Wu and Lee, 2007; Wu *et al.*, 2010; Kim, 2006). The method has found application in several areas as indicated in Table III.

The steps involved in DEMATEL methodology are illustrated in Appendix.

The committee of experts from XYZ machine tools manufacturing company followed our proposed method with the following procedure. First, they defined the decision goals for segmenting the lean criteria into groups in order to facilitate successful lean implementation step by step. Next, the committee adopted the 17 lean criteria as evaluation factors, including: pull system, VSM, IT, 5-S, SMED, visual control, CIM, ERP, job scheduling, standardized work, training, fixed position layout, CM, poka-yoke, smart processes and automation, TQM, and concurrent engineering. Also, they decided to use a 1-5 scale (representing "'no influence,' 'low influence,' 'medium influence,' and 'high influence' and very high influence," respectively) for making assessments. Once the relationships between those factors were measured by the committee through the use of the scale, the data from each individual assessment could be obtained. For example, the assessment data of the general manager of XYZ firm are shown in Table IV. Then, using the average method to aggregate these assessment data, the initial direct-relation matrix (Table V) was produced. In the next

Field	Authors
Supply chain management	Senvar *et al.* (2014), Lin (2013)
Knowledge management	Wu (2008), Patil and Kant (2014)
E-learning programs	Tzeng *et al.* (2007)
Human resource development	Wu and Lee (2007)
Management systems	Tsai and Chou (2009)
Service quality	Tseng (2009b, c), Shieh *et al.* (2010)
Supplier selection	Chang *et al.* (2011), Büyüközkan and Çifçi (2012), Hsu *et al.* (2013), Lirajpour *et al.* (2012)
Emergency management	Zhou *et al.* (2011)
Solid waste management	Tseng (2009)
Animal farming and agriculture	Kim (2006)
Green procurement	Dou *et al.* (2014)
Facility layout planning	Altuntas *et al.* (2014)
Customer's satisfaction	Khosravi *et al.* (2014)
Business process management	Bai and Sarkis (2013)

Table III.
An account of application of DEMATEL by various researchers

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1		3	2	4	1	3	3	4	3	3	1	2	3	2	3	5	2
2	5		2	4	4	5	2	4	1	3	1	4	4	3	2	3	2
3	4	2		3	1	2	4	5	4	3	4	2	2	3	4	4	5
4	3	4	1		3	4	2	3	2	3	2	2	3	2	2	4	1
5	3	4	1	4		2	2	1	1	3	1	2	2	3	3	2	1
6	4	3	1	4	1		3	3	4	3	2	3	3	4	2	3	2
7	4	4	2	4	3	3		4	4	4	3	4	5	3	5	4	3
8	5	3	4	2	1	2	3		4	3	2	3	3	2	4	4	1
9	2	2	1	2	1	3	2	3		2	2	1	1	1	2	3	1
10	3	2	2	3	1	2	2	3	3		4	1	1	1	2	4	1
11	4	4	4	5	4	5	5	4	3	3		2	3	3	4	5	4
12	4	4	1	3	2	2	2	3	2	1	4		4	2	1	3	2
13	4	3	1	3	2	3	2	3	1	1	2	4		3	2	2	2
14	3	2	1	3	4	5	2	3	1	1	1	2	3		3	3	2
15	4	4	2	4	3	3	4	3	3	3	3	3	3	4		4	3
16	4	3	2	5	1	3	2	2	3	5	3	2	3	2	3		2
17	3	4	3	2	3	1	3	1	1	2	2	2	1	1	4	5	

Table IV. Assessment data of the general manager

step, based on the initial direct-relation matrix, the normalized direct-relation matrix (Table VI) was obtained. Next, the total-relation matrix (Table VII) was acquired. Finally, the causal diagram (Figure 1) could be acquired by mapping a data set of (D+R, D−R).

Looking at this causal diagram, it is clear that evaluation factors were visually divided into the cause group, including C3, C7, C8, C11, C12, C15, and C17 while the effect group was composed of such factors as C1, C2, C4, C5, C6, C9, C10, C13, C14, and C16.

From the matrix "T" the threshold value was found to be 0.29. Hence, values in matrix "T" below 0.29 were discarded from further analysis.

The importance of lean criteria was determined by (c+r) values. Based on Table VIII, pull system (C1) and TQM (C16) were the most important lean criteria with the largest (c+r) value = 11.5, whereas job scheduling (P3) was the least important criterion with the smallest (c+r) value = 8.09. With regard to (c+r) values, the prioritization of the importance of 17 lean criteria was C1, C16 > C2, C7 > C11, C15 > C4 > C8 > C6 > C3 > . Considering the (c+r) values, among 17 lean criteria, JIT (C1) and TQM (C16) are the high-priority criteria because they have the highest intensity of relation (11.5) compared to other criteria.

In this empirical study, the case company planned to identify the critical lean criteria before implementation. According to the evaluation results, we can derive several implications about lean implementation as follows.

First, valuable cues can be obtained for making profound decisions from the causal diagram (Figure 1). For example, if we want to obtain high performances in terms of the effect group factors, it would be necessary to control and pay a great deal of attention to the cause group factors beforehand. This is because the cause group factors imply the meaning of the influencing factors, whereas the effect group factors denote the meaning of the influenced factors (Fontela and Gabus, 1976). In other words, the cause group factors are difficult to move, while the effect group factors are easily moved (Hori and Shimizu, 1999).

Table V.
Initial average matrix "A" for the lean criteria in machine tool firms

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	Total
1	0.00	3.80	1.80	3.60	1.40	3.00	3.80	4.20	3.00	3.40	1.60	2.20	3.00	2.00	3.60	4.40	2.00	40.40
2	4.60	0.00	2.60	4.20	4.40	4.00	2.00	4.20	1.40	3.00	1.40	3.40	4.20	3.00	1.40	3.80	1.60	43.80
3	4.20	2.80	0.00	3.00	1.80	2.40	4.20	4.40	3.40	3.40	4.20	1.80	2.00	2.80	3.80	4.40	4.40	44.20
4	2.00	4.20	1.20	0.00	3.20	4.40	1.40	2.60	2.60	3.00	2.40	2.20	4.00	2.20	2.60	4.60	1.80	38.00
5	2.60	4.20	1.40	4.20	0.00	2.00	2.20	1.40	1.20	3.60	1.60	2.20	1.60	3.20	2.80	2.00	1.60	34.20
6	4.60	3.40	1.80	4.20	1.80	0.00	3.00	2.00	4.20	3.20	1.60	3.00	2.40	4.40	3.60	3.00	1.60	43.20
7	4.40	4.40	2.20	4.40	3.00	3.60	0.00	4.80	4.20	4.60	3.00	3.60	4.00	3.00	5.00	4.40	2.60	54.20
8	4.80	3.40	4.60	2.60	1.60	2.60	3.00	0.00	4.60	4.00	1.80	2.40	2.80	2.00	4.60	4.20	1.20	44.80
9	1.80	2.40	1.40	1.80	1.60	3.00	1.80	2.60	0.00	2.00	1.80	1.20	1.20	1.60	2.20	2.60	1.40	26.40
10	2.40	2.20	2.00	2.40	2.00	2.00	1.40	2.00	2.40	0.00	4.60	2.00	1.80	1.60	2.00	4.00	1.00	30.80
11	4.40	4.20	4.40	4.40	4.40	4.60	4.60	3.80	3.60	2.80	0.00	1.80	3.00	3.60	4.00	4.80	4.80	53.60
12	4.00	3.60	1.80	2.40	2.00	2.00	2.60	2.60	2.00	1.60	2.20	0.00	3.80	2.00	1.60	3.00	3.00	34.20
13	4.20	3.40	1.40	3.00	2.60	2.80	2.00	3.00	1.40	1.60	2.20	3.40	0.00	3.00	2.40	2.00	2.00	36.40
14	3.60	2.20	1.40	3.00	3.40	5.00	2.20	3.80	1.40	1.40	1.80	1.60	3.00	0.00	2.20	2.20	2.00	36.00
15	4.60	4.20	2.20	4.80	3.00	3.40	4.00	3.00	3.00	3.20	3.00	2.60	3.00	3.40	0.00	3.80	3.00	47.40
16	4.60	3.60	2.00	4.60	1.60	3.60	3.60	2.00	3.00	4.60	4.00	1.40	4.00	2.00	2.40	0.00	2.00	47.00
17	3.00	4.60	3.00	2.00	3.80	1.40	3.00	1.80	1.80	2.00	2.00	1.60	1.40	1.40	4.60	5.00	0.00	37.40
Total	52.20	48.40	30.20	48.00	36.20	44.80	38.20	44.40	38.40	40.80	33.20	33.40	39.80	37.80	41.80	53.20	34.00	

Table VI. Normalized initial direct-relation matrix "D" for the lean criteria

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	0.00	0.07	0.03	0.06	0.03	0.05	0.07	0.08	0.05	0.06	0.03	0.04	0.05	0.04	0.06	0.08	0.04
2	0.08	0.00	0.05	0.08	0.08	0.07	0.04	0.08	0.03	0.05	0.03	0.06	0.08	0.05	0.03	0.07	0.03
3	0.08	0.05	0.00	0.05	0.03	0.04	0.08	0.08	0.06	0.06	0.08	0.03	0.04	0.05	0.07	0.08	0.08
4	0.04	0.08	0.02	0.00	0.06	0.08	0.03	0.05	0.05	0.05	0.04	0.04	0.07	0.04	0.05	0.08	0.03
5	0.05	0.08	0.03	0.08	0.00	0.04	0.04	0.03	0.02	0.06	0.03	0.04	0.03	0.06	0.05	0.04	0.03
6	0.08	0.06	0.03	0.08	0.03	0.00	0.05	0.04	0.08	0.06	0.03	0.05	0.04	0.08	0.06	0.05	0.03
7	0.08	0.08	0.04	0.08	0.05	0.06	0.00	0.09	0.08	0.08	0.05	0.06	0.07	0.05	0.09	0.08	0.05
8	0.09	0.06	0.08	0.05	0.03	0.05	0.05	0.00	0.08	0.07	0.03	0.04	0.05	0.04	0.08	0.08	0.02
9	0.03	0.04	0.03	0.03	0.03	0.05	0.03	0.05	0.00	0.04	0.03	0.02	0.02	0.03	0.04	0.05	0.03
10	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.04	0.04	0.00	0.08	0.04	0.03	0.03	0.04	0.07	0.02
11	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.07	0.06	0.05	0.00	0.03	0.05	0.06	0.07	0.09	0.09
12	0.07	0.06	0.03	0.04	0.04	0.04	0.05	0.05	0.04	0.03	0.04	0.00	0.07	0.04	0.03	0.05	0.05
13	0.08	0.06	0.03	0.05	0.05	0.05	0.04	0.05	0.03	0.03	0.04	0.06	0.00	0.05	0.04	0.04	0.04
14	0.06	0.04	0.03	0.05	0.06	0.09	0.04	0.07	0.03	0.03	0.03	0.03	0.05	0.00	0.04	0.04	0.04
15	0.08	0.08	0.04	0.09	0.05	0.06	0.07	0.05	0.05	0.06	0.05	0.05	0.05	0.06	0.00	0.07	0.05
16	0.08	0.06	0.04	0.08	0.03	0.06	0.06	0.04	0.05	0.08	0.07	0.03	0.07	0.04	0.04	0.00	0.04
17	0.05	0.08	0.05	0.04	0.07	0.03	0.05	0.03	0.03	0.04	0.04	0.03	0.03	0.03	0.08	0.09	0.00

Table VII.
Total-relation matrix "T" for lean criteria

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	Sum (c)
1	0.32	0.37	0.22[a]	0.36	0.25[a]	0.33	0.31	0.33	0.29	0.32	0.24[a]	0.24[a]	0.30	0.26[a]	0.32	0.38	0.22[a]	5.08
2	0.41	0.31	0.24[a]	0.38	0.30	0.35	0.28[a]	0.34	0.27[a]	0.32	0.24[a]	0.27[a]	0.33	0.28[a]	0.29	0.38	0.22[a]	5.22
3	0.44	0.40	0.22[a]	0.39	0.29	0.35	0.35	0.37	0.33	0.36	0.32	0.26[a]	0.32	0.30	0.37	0.43	0.29	5.80
4	0.34	0.35	0.20[a]	0.28[a]	0.26[a]	0.33	0.25[a]	0.29	0.27[a]	0.30	0.24[a]	0.23[a]	0.30	0.25[a]	0.29	0.36	0.21[a]	4.75
5	0.30	0.32	0.18[a]	0.31	0.18[a]	0.26	0.23[a]	0.24[a]	0.21[a]	0.27[a]	0.20[a]	0.20[a]	0.23[a]	0.24[a]	0.26[a]	0.28[a]	0.18[a]	4.09
6	0.40	0.36	0.22[a]	0.37	0.26[a]	0.28	0.29	0.30	0.31	0.32	0.24[a]	0.25[a]	0.29	0.30	0.32	0.36	0.22[a]	5.08
7	0.48	0.46	0.28[a]	0.46	0.34	0.41	0.31	0.41	0.37	0.41	0.32	0.32	0.39	0.34	0.42	0.47	0.29	6.49
8	0.42	0.38	0.28[a]	0.36[a]	0.27[a]	0.34	0.31	0.28[a]	0.33	0.35	0.26[a]	0.26[a]	0.32	0.27[a]	0.35	0.40	0.23[a]	5.41
9	0.25[a]	0.24[a]	0.15[a]	0.23[a]	0.18[a]	0.23	0.19[a]	0.22[a]	0.16[a]	0.21[a]	0.17[a]	0.16[a]	0.19[a]	0.18[a]	0.21[a]	0.25[a]	0.15[a]	3.37
10	0.29	0.28[a]	0.19[a]	0.28[a]	0.21[a]	0.25	0.22[a]	0.24[a]	0.23[a]	0.21[a]	0.25[a]	0.19[a]	0.23[a]	0.21[a]	0.24[a]	0.31	0.17[a]	3.98
11	0.50	0.48	0.33	0.47	0.37	0.44	0.40	0.41	0.38	0.40	0.29	0.30	0.39	0.36	0.42	0.50	0.34	6.79
12	0.35	0.32	0.20[a]	0.30	0.23[a]	0.27	0.25[a]	0.27[a]	0.24[a]	0.25[a]	0.22[a]	0.18[a]	0.28[a]	0.23[a]	0.25[a]	0.32	0.22[a]	4.38
13	0.35	0.32	0.19[a]	0.31	0.24[a]	0.29	0.24[a]	0.28[a]	0.23[a]	0.25[a]	0.22[a]	0.23[a]	0.22[a]	0.25[a]	0.27[a]	0.30	0.20[a]	4.39
14	0.34	0.30	0.19[a]	0.31	0.25[a]	0.32	0.25[a]	0.29	0.23[a]	0.25[a]	0.21[a]	0.20[a]	0.27[a]	0.20[a]	0.26[a]	0.30	0.20[a]	4.38
15	0.45	0.42	0.26[a]	0.42	0.31	0.37	0.34	0.35	0.32	0.36	0.30	0.28[a]	0.34	0.32	0.30	0.42	0.27[a]	5.83
16	0.41	0.38	0.23[a]	0.39	0.26[a]	0.35	0.31	0.31	0.30	0.35	0.29	0.24[a]	0.33	0.27[a]	0.31	0.33	0.23[a]	5.31
17	0.35	0.36	0.23[a]	0.31	0.27[a]	0.28	0.28[a]	0.27[a]	0.25[a]	0.28[a]	0.23[a]	0.22[a]	0.26[a]	0.23[a]	0.32	0.37	0.18[a]	4.69
Sum (r)	6.40	6.06	3.81	5.94	4.48	5.44	4.82	5.21	4.72	5.21	4.25	4.02	5.00	4.48	5.20	6.23	3.81	

Note: [a]Values below the threshold

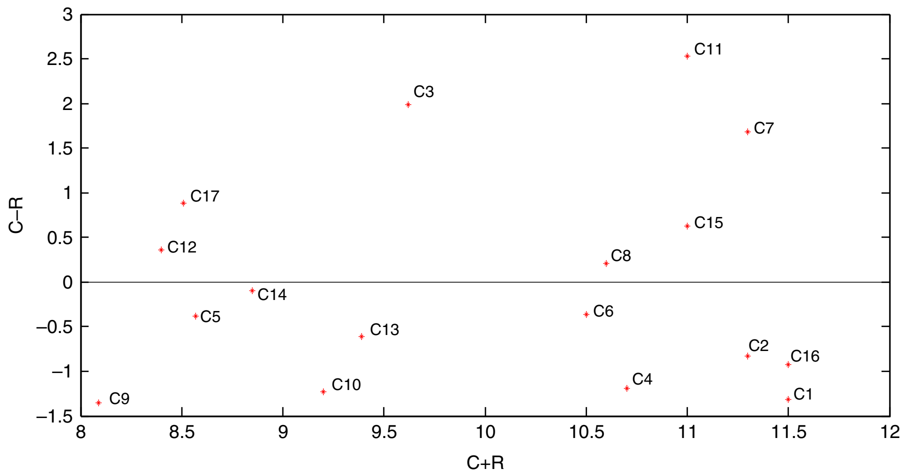

Figure 1.
Overall DEMETAL prominence casual graph

Criteria	Sum (*D*)	Sum (*R*)	Prominence (*D*+*R*)	Net effect (*D*–*R*)	Group
C1	5.08	6.40	11.5	–1.31	Effect
C2	5.22	6.06	11.3	–0.83	Effect
C3	5.8	3.81	9.62	1.99	Cause
C4	4.75	5.94	10.7	–1.19	Effect
C5	4.09	4.48	8.57	–0.38	Effect
C6	5.08	5.44	10.5	–0.36	Effect
C7	6.49	4.82	11.3	1.68	Cause
C8	5.41	5.21	10.6	0.21	Cause
C9	3.37	4.72	8.09	–1.35	Effect
C10	3.98	5.21	9.2	–1.23	Effect
C11	6.79	4.25	11	2.53	Cause
C12	4.38	4.02	8.4	0.36	Cause
C13	4.39	5.00	9.39	–0.61	Effect
C14	4.38	4.48	8.85	–0.1	Effect
C15	5.83	5.2	11	0.63	Cause
C16	5.31	6.23	11.5	–0.92	Effect
C17	4.69	3.81	8.51	0.88	Cause

Table VIII.
Degree of total influence of the lean criteria for experts

Based on (*c*–*r*) values, the 17 lean criteria were divided into two groups: cause group and effect group.

(1) If the value of (*c*–*r*) was positive or net cause, such perspective was classified in the cause group, and directly affected the others. The highest (*c*–*r*) factors also had the greatest direct impact on the others. In this study, IT (C3), CIM (C7), ERP (C8), training (C11), fixed position layout (C12), smart processes and automation (C15) and concurrent engineering (C17) were classified in the cause group, having the (*c*–*r*) values of 1.99, 1.68, 0.21, 2.53, 0.36, and 0.88, respectively. It also indicated that C11 (training) was the most critical impact factor on the other criteria. The training (C11) is the most influencing factor, but it is quite difficult to move. Second, training attempt to increase employees' competencies in order

to make them work better with high performances (Wu and Lee, 2007). Training provides required knowledge and skills to employees for improving performance, at the same time focusses on ways to expand employees' mental ability and brain power. This implies that the effect group can be improved by providing right training.

(2) If the value of $(c-r)$ was negative or net receive, such lean criteria were classified in the effect group, and largely influenced by the others. For this study, JIT (C1), VSM (C2), 5-S (C4), SMED (C5), visual control (C6), job scheduling (C9), standardized work (C10), CM (C13), poka-yoke (C14), and TQM (C16) were categorized in the effect group, with the $(c-r)$ values of −1.31, −0.83, −1.19, −0.38, −0.36, −1.35, −1.21, −0.61, −0.1, and −0.92, respectively. And job scheduling (C9) was the most affected by the other factors C3, C7, C8, C11, C12, C15, and C17.

4. Conclusions and implications

To help reduce lean implementation failure rate, lean implementation issues are currently receiving significant practical and research attention. Firms need to pay careful attention to select the right lean criteria and appropriate lean models. However, a lean model often contains a list of numerous lean criteria. Initially we used the literature to identify the critical lean criteria which were then validated by experts of XYZ machine tool manufacturing company. Although this paper cannot claim to be exhaustive in its review of criteria, the framework does provide a comprehensive set of the lean implementation criteria and highlights the relationships that are likely to exist between the lean criteria.

There arises an important issue in terms of segmenting the set of lean criteria into some meaningful portions in order to effectively facilitate its implementation. Additionally, to handle this issue, it is also necessary to solve the matter of integrating group decisions. Hence, we proposed the DEMATEL method to achieve segmentation of required lean criteria for effective implementation. Our proposed methodology successfully employs the DEMATEL method for XYZ machine tool manufacturing company. The methodology proved quite useful in integrating the perceptions and perspectives of various company experts. We arrived at a series of results, and the methodology provided some strategic scenarios of the relationships of the lean criteria. This method can also successfully divide a set of complex factors into cause and effect groups through a visible causal diagram. Through the causal diagram, the complexity of a problem is easier to capture, whereby profound decisions can be made.

As concerns our empirical study, the proposed DEMATEL method worked smoothly in tackling the issue of segmenting the 17 lean criteria into meaningful portions. According to the analysis results, seven lean criteria lie in the cause group so the management must pay greater attention and commit resources for their development. These include IT, CIM, ERP, training, fixed position layout, smart processes and automation, and concurrent engineering.

The results of the evaluation of the field study company provided some initial insights into importance of lean criteria and the sequencing of these criteria. By the aspect of prioritizing the importance of criteria and the cause and effect relationship among criteria, this study found that the JIT, TQM and training were the most critical criteria. Therefore, in order to enhance the overall competitive potential in term of lean implementation, Indian manufacturing firms should initially allocate more resources in these core criteria. In the lean implementation process, firms should emphasize on training since it is the main critical criterion that would yield highest positive impact on other criteria.

Even though we believe that our proposed DEMATEL method is comprehensive and applicable to all manufacturing firms facing problems that require group decision making to segment complex criteria, limitation that leave scope of further research exists. For future research, one possible direction may be to research a more satisfying fuzzy aggregation method. Also, data can be collected from a number of companies from inside and outside India for better generalization of results. Further, empirical work can be undertaken to test the approach and verify the transferability of results to other countries and industries. Introducing sub-criteria and additional lean criteria can provide added insight to lean implementation tactical and operational issues. Even though some limitations and disadvantages do exist, there is ample opportunity to investigate how this tool can be used to expand lean implementation.

Glossary

CIM	Computer-integrated manufacturing
CNC	Computer numerical control
DEMATEL	Decision-Making Trial and Evaluation Laboratory
ERP	Enterprise resource planning
ISO	International organization of standardization
IT	Information technology
JIT	Just in time
LM	Lean manufacturing
LMS	Lean manufacturing system
SMED	Single minute exchange of die
SMEs	Small and medium enterprises
TQM	Total quality management
VSM	Value stream mapping
WIP	Work-in-process

References

Achanga, P., Shehab, E., Roy, R. and Nelder, G. (2006), "Critical success factors for lean implementation within SMEs", *Journal of Manufacturing Technology Management*, Vol. 17 No. 4, pp. 460-471.

Ahmad, S. and Azuan, S. (2013), "Culture and lean manufacturing: towards a holistic framework", *Australian Journal of Basic and Applied Sciences*, Vol. 7 No. 1, pp. 334-338.

Altuntas, S., Selim, H. and Dereli, T. (2014), "A fuzzy DEMATEL-based solution approach for facility layout problem: a case study", *The International Journal of Advanced Manufacturing Technology*, pp. 1-23.

April, J., Powell, D. and Bart, S. (2010), "A new lean change methodology for small & medium sized enterprises", *12th International MITIP Conference on Information Technology & Innovation Processes of the Enterprises (MITIP-2010), Aalborg University*, pp. 27-35.

Arora, P.K., Haleem, A., Singh, M.K. and Kumar, H. (2013), "Proposed model for optimizing production system using CMS", *Applied Mechanics and Materials*, Vol. 281, pp. 673-676.

Bai, C. and Sarkis, J. (2013), "A grey-based DEMATEL model for evaluating business process management critical success factors", *International Journal of Production Economics*, Vol. 146 No. 1, pp. 281-292.

Balle, M. (2005), "Lean attitude", available at: http://michaelballe.fr/papers/LeanAttitude.pdf (accessed June 3, 2013).

Bamber, L. and Dale, B.G. (2000), "Lean production: a study of application in a traditional manufacturing environment", *Production Planning and Control*, Vol. 11 No. 3, pp. 291-298.

Bayou, M.E. and De Korvin, A. (2008), "Measuring the leanness of manufacturing systems – a case study of Ford motor company and general motors", *Journal of Engineering and Technology Management*, Vol. 25 No. 4, pp. 287-304.

Belokar, R.M., Kharb, S.S. and Kumar, V. (2012), "An application of value stream mapping in automobile industry: a case study", *International Journal of Innovative Technology and Exploring Engineering (IJITEE)*, Vol. 1 No. 2, pp. 231-236.

Bhamu, J., Kumar, J.S. and Sangwan, K.S. (2012), "Productivity and quality improvement through value stream mapping: a case study of Indian automotive industry", *International Journal of Productivity and Quality Management*, Vol. 10 No. 3, pp. 288-306.

Braglia, M., Carmignani, G. and Zammori, F. (2006), "A new value stream mapping approach for complex production systems", *International Journal of Production Research*, Vol. 44 No. 18, pp. 3929-3952.

Brintrup, A., Ranasinghe, D. and McFarlane, D. (2010), "RFID opportunity analysis for leaner manufacturing", *International Journal of Production Research*, Vol. 48 No. 9, pp. 2745-2764.

Büyüközkan, G. and Çifçi, G. (2012), "A novel hybrid MCDM approach based on fuzzy DEMATEL, fuzzy ANP and fuzzy TOPSIS to evaluate green suppliers", *Expert Systems with Applications*, Vol. 3 No. 3, pp. 3000-3011.

Carrizo, M.A. and Campos, S.P.G. (2011), "Single minute exchange of die: a case study implementation", *Journal of Technology Management and Innovation*, Vol. 6 No. 1, pp. 129-146.

Chang, B., Chang, C.W. and Wu, C.H. (2011), "Fuzzy DEMATEL method for developing supplier selection criteria", *Expert Systems with Applications*, Vol. 38 No. 3, pp. 1850-1858.

Cottyn, J., Landeghem, H.V., Stockman, K. and Derammelaere, S. (2011), "A method to align a manufacturing execution system with lean objectives", *International Journal of Production Research*, Vol. 49 No. 14, pp. 4397-4413.

Crute, V., Ward, Y., Brown, S. and Graves, A. (2003), "Implementing lean in aerospace – challenging the assumptions and understanding the challenges", *Technovation*, Vol. 23 No. 12, pp. 917-928.

Dave, B.A. (2013), "Developing a construction management system based on lean construction and building information modeling", doctoral dissertation, University of Salford, Manchester.

Devadasan, S.R., Sivakumar, M.V., Murugesh, R. and Shalij, P.R. (2012), *Lean and Agile Manufacturing Theoretical, Practical and Research Futurities*, PHI Learning, New Delhi.

Dixit, A.R. and Mishra, P.K. (2008), "Design of flexible manufacturing cell considering uncertain product mix requirement", *International Journal of Agile Systems and Management*, Vol. 3 No. 1, pp. 37-60.

Doolen, T.L. and Hacker, M.E. (2005), "A review of lean assessment in organizations: an exploratory study of lean practices by electronics manufacturers", *Journal of Manufacturing Systems*, Vol. 24 No. 1, pp. 55-67.

Dou, Y., Sarkis, J. and Bai, C. (2014), *Government Green Procurement: A Fuzzy-DEMATEL Analysis of Barriers, Supply Chain Management Under Fuzziness*, Springer, Berlin Heidelberg, pp. 567-589.

Dunstan, K., Lavin, B. and Sanford, R. (2006), "The application of lean manufacturing in a mining environment", *Proceedings of the International Mine Management Conference, Melbourne, October 6-18*, pp. 145-157.

Eswaramoorthi, M., Kathiresan, G.R., Prasad, P.S.S. and Mohanram, P.V. (2011), "A survey on lean practices in Indian machine tool industries", *The International Journal of Advanced Manufacturing Technology*, Vol. 52 Nos 9-12, pp. 1091-1101.

Fontela, E. and Gabus, A. (1976), "The DEMATEL observer, DEMATEL 1976 report", Battelle Geneva Research Center, Geneva.

Forza, C. (1996), "Work organization in lean production and traditional plants: what are the differences?", *International Journal of Operations and Production Management*, Vol. 16 No. 2, pp. 42-62.

Genaidy, A.M. and Karwowski, W. (2003), "Human performance in lean production environment: critical assessment and research framework", *Human Factors and Ergonomics in Manufacturing and Service Industries*, Vol. 13 No. 4, pp. 317-330.

Groover, M.P. (2011), *Automation, Production Systems, and Computer-Integrated Manufacturing*, Prentice Hall Press, New Delhi.

Gurumurthy, A. and Kodali, R. (2011), "Design of lean manufacturing systems using value stream mapping with simulation: a case study", *Journal of Manufacturing Technology Management*, Vol. 22 No. 4, pp. 444-473.

Hallam, C.R. and Keating, J. (2014), "Company self-assessment of lean enterprise maturity in the aerospace industry", *Journal of Enterprise Transformation*, Vol. 4 No. 1, pp. 51-71.

Haque, B. and Moore, M.J. (2004), "Measures of performance for lean product introduction in the aerospace industry", *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, Vol. 218 No. 10, pp. 1387-1398.

Hasle, P. (2014), "Lean production – an evaluation of the possibilities for an employee supportive lean practice", *Human Factors and Ergonomics in Manufacturing and Service Industries*, Vol. 24 No. 1, pp. 40-53.

Herron, C. and Hicks, C. (2008), "The transfer of selected lean manufacturing techniques from Japanese automotive manufacturing into general manufacturing (UK) through change agents", *Robotics and Computer-Integrated Manufacturing*, Vol. 24 No. 4, pp. 524-531.

Hines, P. and Taylor, D. (2000), *Going Lean*, Lean Enterprise Research Centre Cardiff Business School, Cardiff.

Hori, S. and Shimizu, Y. (1999), "Designing methods of human interface for supervisory control systems", *Control Engineering Practice*, Vol. 7 No. 11, pp. 1413-1419.

Hsu, C.W., Kuo, T.C., Chen, S.H. and Hu, A.H. (2013), "Using DEMATEL to develop a carbon management model of supplier selection in green supply chain management", *Journal of Cleaner Production*, Vol. 56, pp. 164-172.

Hsu, C.Y., Chen, K.T. and Tzeng, G.H. (2007), "FMCDM with fuzzy DEMATEL approach for customers' choice behavior model", *International Journal of Fuzzy Systems*, Vol. 9 No. 4, pp. 236-246.

Imam, A.T. and Sudipto Sarkar, S. (2012), "Lean sigma a road to success: a perspective of the indian automobile industry", *Global Journal of Researches in Engineering*, Vol. 12 Nos 1-A, pp 51-59.

James-Moore, S.M. and Gibbons, A. (1997), "Is lean manufacture universally relevant? An investigative methodology", *International Journal of Operations and Production Management*, Vol. 17 No. 9, pp. 899-911.

Jeyaraman, K. and Teo, L.K. (2010), "A conceptual framework for critical success factors of lean six sigma: implementation on the performance of electronic manufacturing service industry", *International Journal of Lean Six Sigma*, Vol. 1 No. 3, pp. 191-215.

Kajdan, V. (2008), "Bumpy road to lean enterprise", *Total Quality Management and Business Excellence*, Vol. 19 Nos 1-2, pp. 91-99.

Kallange, R. (2006), "Lean implementation failures", available at: www.thefabricator.com/article/shopstrategies/lean-implementation-failures (accessed June 3, 2013).

Kalpakjian, S. and Schmid, S.R. (2009), *Manufacturing Processes for Engineering Materials*, Pearson Education, New Delhi.

Karthi, S., Devadasan, S.R. and Murugesh, R. (2011), "Lean six sigma through ISO 9001 standard-based quality management system: an investigation for research", *International Journal of Productivity and Quality Management*, Vol. 8 No. 2, pp. 180-204.

Khosravi, M.A., Najafi, S.E., Lak, H. and Khosravi, M. (2014), "A study of factors affecting customer's satisfaction with fuzzy DEMATEL method", *Asian Journal of Research in Marketing*, Vol. 3 No. 1, pp. 46-60.

Kim, Y.H. (2006), "Study on impact mechanism for beef cattle farming and importance of evaluating agricultural information in Korea using DEMATEL, PCA and AHP", *Agricultural Information Research*, Vol. 15 No. 3, pp. 267-280.

Kuhlang, P., Hempen, S., Sihn, W. and Deuse, J. (2013), "Systematic improvement of value streams-fundamentals of value stream oriented process management", *International Journal of Productivity and Quality Management*, Vol. 12 No. 1, pp. 1-17.

Kumar, M., Antony, J., Singh, R.K., Tiwari, M.K. and Perry, D. (2006), "Implementing the Lean sigma framework in an Indian SME: a case study", *Production Planning and Control*, Vol. 17 No. 4, pp. 407-423.

Lee, M.C. and Chang, T. (2010), "Developing a lean design for six sigma through supply chain methodology", *International Journal of Productivity and Quality Management*, Vol. 6 No. 4, pp. 407-434.

Lee, Y.C., Yen, T.M. and Tsai, C.H. (2008), "Using importance-performance analysis and decision making trial and evaluation laboratory to enhance order-winner criteria – a study of computer industry", *Information Technology Journal*, Vol. 7 No. 3, pp. 396-408.

Leon, A. (2008), *Enterprise Resource Planning*, Tata McGraw-Hill Education, New Delhi.

Li, C.W. and Tzeng, G.H. (2009), "Identification of interrelationship of key customers' needs based on structural model for services/capabilities provided by a semiconductor-intellectual-property mall", *Applied Mathematics and Computation*, Vol. 215 No. 6, pp. 2001-2010.

Liang, D. and Wang, H. (2013), "Study on the development strategy of lean logistics for automobile enterprises under green supply chain environment", *Applied Mechanics and Materials*, Vol. 397, pp. 2677-2680.

Lin, Y.-T., Yang, Y.H., Kang, J.S. and Yu, H.C. (2011), "Using DEMATEL method to explore the core competences and causal effect of the IC design service company: an empirical case study", *Expert Systems with Applications*, Vol. 38 No. 5, pp. 6262-6268.

Lin, C.J. and Wu, W.W. (2008), "A causal analytical method for group decision-making under fuzzy environment", *Expert Systems with Applications*, Vol. 34, pp. 205-213.

Lin, R.J. (2013), "Using fuzzy DEMATEL to evaluate the green supply chain management practices", *Journal of Cleaner Production*, Vol. 40, pp. 32-39.

Liou, J.J.H., Yen, L. and Tzeng, G.H. (2007), "Building an effective safety management system for airlines", *Journal of Air Transport Management*, Vol. 14, pp. 20-26.

Lirajpour, A., Hajimirza, M., Alavi, M.G. and Kazemi, S. (2012), "Identification and evaluation of the most effective factors in green supplier selection using DEMATEL method", *Journal of Basic and Applied Scientific Research*, Vol. 2 No. 5, pp. 4485-4493.

Mandal, P. and El-Houbi, A. (2009), "Business practices and information strategy in performance improvement", *International Journal of Productivity and Quality Management*, Vol. 4 No. 5, pp. 715-729.

Martínez-Jurado, P.J. and Moyano-Fuentes, J. (2014), "Key determinants of lean production adoption: evidence from the aerospace sector", *Production Planning and Control*, Vol. 25 No. 4, pp. 332-345.

Mathaisel, D.F. (2005), "A lean architecture for transforming the aerospace maintenance, repair and overhaul (MRO) enterprise", *International Journal of Productivity and Performance Management*, Vol. 54 No. 8, pp. 623-644.

McIntosh, R.I., Culley, S.J., Mileham, A.R. and Owen, G.W. (2000), "A critical evaluation of Shingo's SMED (Single Minute Exchange of Die) methodology", *International Journal of Production Research*, Vol. 38 No. 11, pp. 2377-2395.

McManus, H.L., Haggerty, A. and Murman, E. (2007), "Lean engineering: a framework for doing the right thing right", *Aeronautical Journal*, Vol. 111 No. 1116, pp. 105-114.

Melton, T. (2005), "The benefits of lean manufacturing: what lean thinking has to offer the process industries?", *Chemical Engineering Research and Design*, Vol. 83 No. 6, pp. 662-673.

Michael, G.S., Devadasan, S.R. and Shalij, P.R. (2010), "Current state maps on the implementation of lean and six-sigma paradigms and an exclusive model for deploying lean six-sigma in SMEs", *International Journal of Productivity and Quality Management*, Vol. 5 No. 3, pp. 286-309.

Michaels, L.M.J. (1999), "The making of a lean aerospace supply chain", *Supply Chain Management: An International Journal*, Vol. 4 No. 3, pp. 135-145.

Mohanraj, R., Sakthivel, M. and Vinodh, S. (2011), "QFD integrated value stream mapping: an enabler of lean manufacturing", *International Journal of Productivity and Quality Management*, Vol. 7 No. 4, pp. 501-522.

Mohanty, R.P., Yadav, O.P. and Jain, R. (2007), "Implementation of lean manufacturing principles in auto industry", *Vilakshan – XIMB Journal of Management*, Vol. 1, pp. 1-32.

Oppenheim, B.W., Murman, E.M. and Secor, D.A. (2011), "Lean enablers for systems engineering", *Systems Engineering*, Vol. 14 No. 1, pp. 29-55.

Panizzolo, R., Garengo, P., Sharma, M.K. and Gore, A. (2012), "Lean manufacturing in developing countries: evidence from Indian SMEs", *Production Planning and Control: The Management of Operations*, Vol. 23 Nos 10-11, pp. 769-788.

Paranitharan, K.P., Begam, M.S., Abuthakeer, S.S. and Subha, M.V. (2011), "Redesigning an automotive assembly line through lean strategy", *International Journal of Lean Thinking*, Vol. 2 No. 2, pp. 1-14.

Parry, G.C. and Turner, C.E. (2006), "Application of lean visual process management tools", *Production Planning and Control: The Management of Operations*, Vol. 17 No. 1, pp. 77-86.

Patil, S.K. and Kant, R. (2014), "A hybrid approach based on fuzzy DEMATEL and FMCDM to predict success of knowledge management adoption in supply chain", *Applied Soft Computing*, Vol. 18, pp. 126-135.

Pavnaskar, S.J., Gershenson, J.K. and Jambekar, A.B. (2003), "Classification scheme for lean manufacturing tools", *International Journal of Production Research*, Vol. 41 No. 13, pp. 3075-3090.

Petersen, K. (2012), *'A Palette of Lean Indicators to Detect Waste in Software Maintenance: A Case Study', Agile Processes in Software Engineering and Extreme Programming*, Springer, Berlin Heidelberg, pp. 108-122.

Phan, C.A. and Matsui, Y. (2010), "Contribution of quality management and just-in-time production practices to manufacturing performance", *International Journal of Productivity and Quality Management*, Vol. 6 No. 1, pp. 23-47.

Pullan, T.T., Bhasi, M. and Madhu, G. (2011), "Decision support tool for lean product and process development", *Production Planning and Control: The Management of Operations*, Vol. 24 No. 6, pp. 449-464, doi: 10.1080/09537287.2011.633374.

Raveendra, L.M. (n.d.), "Failure factors in lean implementation: case study at Loadstar (Pvt.) Ltd", available at: http://dl.lib.mrt.ac.lk/theses/handle/123/1468 (accessed June 1, 2013).

Sahay, B.S., Sharma, V. and Sardana, G.D. (2011), "Supply chain management practices of indian automobile industry", *International Journal of Information Systems and Supply Chain Management*, Vol. 4 No. 3, pp. 60-78.

Sánchez, A.M. and Pérez, M.P. (2001), "Lean indicators and manufacturing strategies", *International Journal of Operations and Production Management*, Vol. 21 No. 11, pp. 1433-1452.

Scheer, A.W. (2012), *CIM Computer Integrated Manufacturing: Computer Steered Industry*, Springer Publishing Company Inc., New York, NY.

Senvar, O., Tuzkaya, U.R. and Kahraman, C. (2014), *Supply Chain Performance Measurement: An Integrated DEMATEL and Fuzzy-ANP Approach, Supply Chain Management Under Fuzziness*, Springer, Berlin Heidelberg, pp. 143-165.

Shah, R. and Ward, T. (2007), "Defining and developing measures of lean production", *Journal of Operations Management*, Vol. 25 No. 4, pp. 785-805.

Sharma, S.K., Gupta, R.D., Kumar, A. and Singh, B. (2011), "Supplier issues for lean implementation", *International Journal of Engineering Science and Technology*, Vol. 3 No. 5, pp. 3900-3905.

Sharma, V., Dixit, A.R., Qadri, M.A. and Kumar, S. (2015), "An interpretive hierarchical model for lean implementation in machine tool sector", *International Journal of Productivity and Quality Management*, Vol 15 No. 3, pp. 381-406.

Sharma, V., Sahay, B.S. and Sardana, G.D. (2008), "An empirical assessment of the impact of SCM practices on quality performance: a case in the Indian automobile industry", *Supply Chain Forum: An International Journal*, Vol. 9 No. 1, pp. 28-40.

Shieh, J.I., Wu, H.H. and Huang, K.K. (2010), "A DEMATEL method in identifying key success factors of hospital service quality", *Knowledge-Based Systems*, Vol. 23 No. 3, pp. 277-282.

Shingo, S. (1985), *A Revolution in Manufacturing: The SMED System*, Productivity Press, New York, NY.

Singh, B. and Sharma, S.K. (2009), "Value stream mapping a versatile tool for lean implementation: an Indian case study of a manufacturing industry", *Journal of Measuring Business Excellence*, Vol. 13 No. 3, pp. 58-68.

Singh, B., Garg, S.K., Sharma, S.K. and Grewal, C. (2010), "Lean implementation and its benefits to production industry", *International Journal of Lean Six Sigma*, Vol. 1 No. 2, pp. 157-168.

Slack, R.A. (1998), "The application of lean principles to the military aerospace product development process", doctoral dissertation, Massachusetts Institute of Technology, Cambridge.

Tsai, W.H. and Chou, W.C. (2009), "Selecting management systems for sustainable development in SMEs: a novel hybrid model based on DEMATEL, ANP, and ZOGP", *Expert Systems with Applications*, Vol. 36, pp. 1444-1458.

Tseng, M.L. (2009a), "A causal and effect decision making model of service quality expectation using grey-fuzzy DEMATEL approach", *Expert Systems with Applications*, Vol. 36 No. 4, pp. 7738-7748.

Tseng, M.L. (2009b), "Application of ANP and DEMATEL to evaluate the decision-making of municipal solid waste management in Metro Manila", *Environmental Monitoring and Assessment*, Vol. 156 Nos 1-4, pp. 181-197.

Tseng, M.L. (2009c), "Using the extension of DEMATEL to integrate hotel service quality perceptions into a cause – effect model in uncertainty", *Expert Systems with Applications*, Vol. 36 No. 5, pp. 9015-9023.

Tzeng, G.H., Chiang, C.H. and Li, C.W. (2007), "Evaluating intertwined effects in e-learning programs: a novel hybrid MCDM model based on factor analysis and DEMATEL", *Expert Systems with Applications*, Vol. 32 No. 4, pp. 1028-1044.

Vinodh, S., Gautham, S.G. and Ramiya, R.A. (2011), "Implementing lean sigma framework in an Indian automotive valves manufacturing organisation: a case study", *Production Planning and Control*, Vol. 22 No. 7, pp. 708-722.

Von Axelson, J. (2009), "Developing lean production implementation methodology for SME learning networks", *16th International Annual EurOMA Conference*, pp. 14-17.

Wang, C.H., Kao, J.H. and Hsu, M.T. (2012), "Implementation of lean model for carrying out value stream mapping in the aerospace engine case production", *Advanced Science Letters*, Vol. 13 No. 1, pp. 697-701.

Winter, D., Jones, C., Ward, C., Gibbons, P., McMahon, C. and Potter, K. (2013), *'The Application of a Lean Philosophy During Manufacture of Advanced Airframe Structures in a New Product Introduction (NPI) environment', Advances in Sustainable and Competitive Manufacturing Systems*, Springer International Publishing, pp. 1503-1513.

Womack, J.P. and Jones, D.T. (2003), *Banish Waste and Create Wealth in Your Corporation*, Free Press, New York, NY.

Wong, Y.C. and Wong, K.Y. (2011), "Approaches and practices of lean manufacturing: the case of electrical and electronics companies", *African Journal of Business Management*, Vol. 5 No. 6, pp. 2164-2174.

Wu, H.-H. and Tsai, Y.-N. (2011), "A DEMATEL method to evaluate the causal relations among the criteria in auto spare parts industry", *Applied Mathematics and Computation*, Vol. 218, pp. 2334-2342.

Wu, H.H., Chen, H.K. and Shieh, J.I. (2010), "Evaluating performance criteria of employment service outreach program personnel by DEMATEL method", *Expert Systems with Applications*, Vol. 37 No. 7, pp. 5219-5223.

Wu, W.W. (2008), "Choosing knowledge management strategies by using a combined ANP and DEMATEL approach", *Expert Systems with Applications*, Vol. 35 No. 3, pp. 828-835.

Wu, W.W. and Lee, Y.T. (2007), "Developing global managers' competencies using the fuzzy DEMATEL method", *Expert Systems with Applications*, Vol. 32 No. 2, pp. 499-507.

Yassine, A. and Braha, D. (2003), "Complex concurrent engineering and the design structure matrix method", *Concurrent Engineering*, Vol. 11 No. 3, pp. 165-176.

Zhou, Q., Huang, W. and Zhang, Y. (2011), "Identifying critical success factors in emergency management using a fuzzy DEMATEL method", *Safety Science*, Vol. 49 No. 2, pp. 243-252.

Appendix

The steps of DEMATEL method are enumerated as follows:

Step 1: using the data collected from experts, compute the average matrix. Each respondent is asked to evaluate the direct influence between any two factors by an integer score ranging from 1 to 5, representing "'no influence,' 'low influence,' 'medium influence,' and 'high influence'" and very high influence, respectively. The notation of x_{ij} indicates the degree to which the respondent believes factor i affects factor j. For $i=j$, the diagonal elements are set to zero, indicating no influence. For each respondent, an $n \times n$ non-negative matrix can be established as $X^k = x_{ij}^k$, where k is the number of respondents with $1 \leqslant k \leqslant H$, and n is the number of factors. Thus, $X^1, X^2, X^3, \ldots, X^H$ are the matrices from H respondents. To incorporate all opinions from H respondents, the average matrix $A=[a_{ij}]$ can be constructed as follows:

$$a_{ij} = \frac{1}{H}\sum_{k=1}^{H} x_{ij}^k$$

$$a_{ij} = \frac{1}{H}$$

Step 2: compute the normalized initial direct-relation matrix. Normalize initial direct-relation matrix D by $D=A\times S$, where:

$$S = \frac{1}{\max_{1 \leqslant i \leqslant n} \sum_{j=1}^{n} a_{ij}}$$

Each element in matrix D falls between zero and one.

Step 3: determine the total-relation matrix. The total-relation matrix T is defined as $T=D(I-D)^{-1}$, where I is the identity matrix. Define r and c by $n\times 1$ and $1\times n$ vectors representing the sum of rows and sum of columns of the total-relation matrix T, respectively. Suppose r_i be the sum of ith row in matrix T, then r_i summarizes both direct and indirect effects given by factor i to the other factors. If c_j denotes the sum of jth column in matrix T, then c_j shows both direct and indirect effects by factor j from the other factors. When $j=i$, the sum (c_j+r_i) shows the total effects given and received by factor i. Thus, (c_j+r_i) indicates the degree of importance for factor i in the entire system. On the contrary, the difference (c_j-r_i) represents the net effect that factor i contributes to the system. Specifically, if (c_j-r_i) is positive, factor i is a net cause, while factor i is a net receiver or result if (c_j-r_i) is negative (Lee *et al.*, 2008).

Step 4: set up a threshold value to obtain the digraph. Since matrix T provides information on how one factor affects another, it is necessary for a decision maker to set up a threshold value to filter out some negligible effects. In doing so, only the effects greater than the threshold value would be chosen and shown in digraph. In this study, the threshold value is set up by computing the average of the elements in matrix T. The digraph can be acquired by mapping the data set of $(c+r, c-r)$.

About the authors

Vikram Sharma is currently serving as an Associate Professor of Mechanical & Mechatronics Engineering in the The LNM Institute of Information Technology, Jaipur, India. He has over 14 years of teaching and research experience. He has presented several papers in international conferences and journals. His current research interests include supply chain modeling and lean manufacturing.

Amit Rai Dixit is serving as an Associate Professor of Mechanical Engineering in the Indian School of Mines Dhanbad, India. He has over ten years of teaching and research experience. He holds a BTech degree in mechanical engineering, and ME degree in production and PhD in the field of cellular manufacturing systems. He has presented several papers in

international conferences and journals. His current research interest includes advanced production systems

Mohammad Asim Qadri is a Professor in Mechanical Engineering Department of Galgotias College of Engineering and Technology, Greater Noida, India. He did his BSc in Mechanical Engineering and MSc in Mechanical Engineering from Jamia Millia Islamia, New Delhi and Aligarh Muslim University, Aligarh, respectively. He obtained his PhD from Jamia Millia Islamia in the area of green supply chain management. His research interests include green supply chain management, optimization techniques, operations management among others