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ORIGINAL ARTICLE

A dynamic modeling to measure lean performance within lean attributes

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Abstract In today's competitive world lean manufacturing has become an important "role model" for two groups: academics and practitioners. Many organizations around the world have attempted to implement it but the lack of a clear understanding of the main attributes to leanness, lean performance and its measurement contribute to the failure of lean practices. It therefore seems necessary to provide a way to evaluate the impact of lean attributes using an approach to determine the criteria and key factors of leanness. Although there are numerous theoretical and practical studies that address lean tools and techniques, few studies focus systematically on measuring the influence of lean attributes on leanness. To fill the current gap, this paper presents an innovative approach to measure the value of the influence of lean attributes on manufacturing systems by using fuzzy membership functions. A lean attributes score is finally calculated to give managers and decision makers a real insight into the leanness level and to further improve it by acting appropriately in the manufacturing system. The model is dynamic, flexible, feasible, and easy to follow and implement. It enables a systematic measurement of the influence of lean attributes by producing a final integrated unit score.

Keywords Lean manufacturing · Lean performance · Lean attributes · Fuzzy logic · Dynamic scheduling

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1 Introduction

Nowadays, most companies around the world are willing to improve and develop their ability for competition, for which lean manufacturing (LM) is one of the approaches. However, not all of those which are willing to use this approach have been succeeded in their endeavor. One of the main reasons is the lack of a clear understanding of lean attributes and their influence is a significant cause of failure in lean practices. In other words, it is not possible to manage lean without identifying a way to measure the impact of attributes that influence leanness.

LM is "lean" because it uses less of everything compared with mass production: half the human effort in a factory, half the manufacturing space, half the investment in tools, half the engineering hours to develop a new product in half the time. Also, it requires keeping far less than half the needed inventory on site, results in lesser defects, and produces a greater and ever growing variety of products [1]. Such a rigorous process benefits customers by weeding out defective products and services, shortening lead times, and reducing costs [2].

Kulaka et al. [3] proposed a road map (with assessment system and improvement system) for people who want to transform their traditional production system from process orientation to cellular orientation. Anvari et al. [4] compared more than 20 procedures to implement LM, as well proposing a roadmap to leanness [5]. Furthermore, Yimer and Demirli [6] proposed two models of leanness and agility approach, to minimize the aggregate costs associated with each subsystem, while meeting customer service requirements as well as efforts to broaden market share. In addition, Rubio and Corominas [7] suggested a model in a LM environment, based on economic order quantity for best manufacturing.

So, to improve the design of a manufacturing system, it is necessary to know the crucial performance metrics of the system including cost, lead time, downtimes and wait times, and so on, and to identify the effects of design parameters on system performance [8]. In this regard, Wan and Chen [9] to evaluate performance, consider cost, time, and value, which are

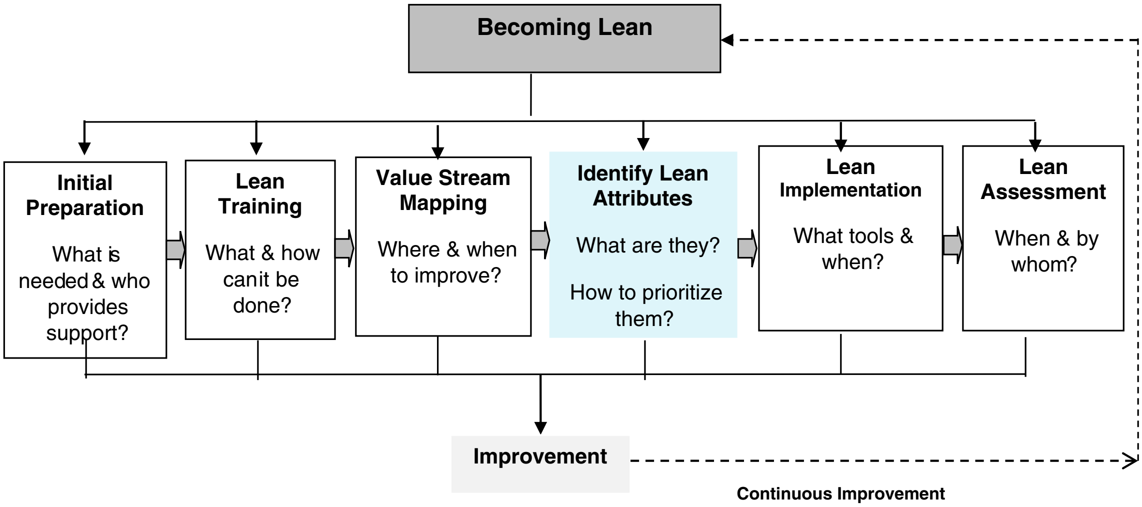

Fig. 1 Main phases of a typical leanness cycle

selected as variables, and a fourth factor (quantitative) is defect that is explored after products are delivered to the customer.

This paper presents a quantitative model to measure the criteria impacts on LM systems. Using fuzzy membership functions, lean attribute measures are quantified by comparing their current effects to the benchmarks derived from historical data. A lean attributes score is finally calculated to give managers and decision makers (DMs) a real insight into the lean performance level and to further improve it by taking appropriate actions in the manufacturing system. In this paper, we apply the above method to the evaluation of lean attributes taking into account leanness under aggregating environments wherein the useful procedure is analyzed for different conditions and components.

The paper is organized as follows. In the next section, we review the lean assessment literature. In Section 3 we explain how to determine lean attributes. The fuzzy method is indicated and applied in Section 4 for a given application. The proposed measurement method is presented in Section 5 and numerical examples of the model are given in Section 6. An alternative method is described, and a case study is presented in Section 7. Finally, the paper concludes with a discussion and conclusion section that incorporates the main findings of the paper.

2 Literature review

2.1 Leanness and measurement

The term leanness has been used by several researchers while discussing LM. However, the perceptions of leanness found in the literature differ from one author to another. The definition of leanness was not stated explicitly by various

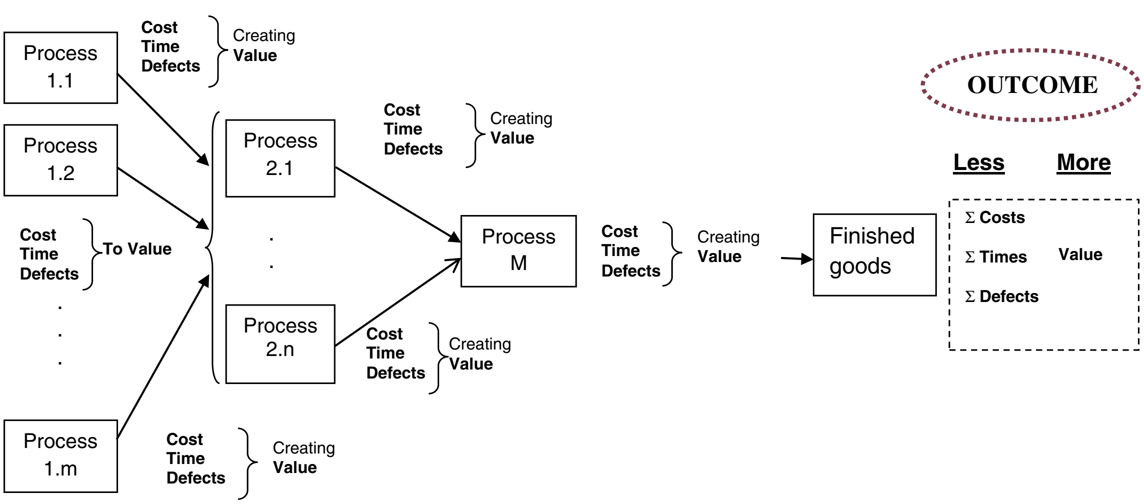

Fig. 2 Main variables to lean attributes in leanness process

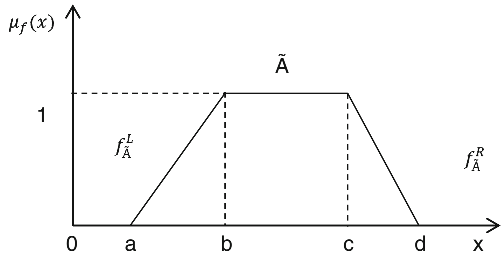

Fig. 3 Membership functions of trapezoidal fuzzy numbers

researchers [10, 11]; their opinions are reviewed in this section. Comm and Mathaisel [12] describe leanness as a relative measure of whether a company is lean or not. They also stated that "leanness is a philosophy intended to significantly reduce cost and cycle time throughout the entire value chain while continuing to improve product performance." Leanness is developing a value stream to eliminate all waste, including time, and to ensure a level schedule [13–15].

The term "total leanness" was used by McIvor [16] to imply a perfectly lean state of several key dimensions of lean supply. Soriano-Meier and Forrester [17] developed a model with nine variables to evaluate the degree of leanness of manufacturing firms. Anvari et al. [4] attempted to outline the concept of leanness by reviewing the previous uses of the word. Finally, Vinodh and Balaji [18] developed a leanness assessment based on fuzzy logic and in another study; leanness assessment was performed using a multi-grade fuzzy approach [19]. Moreover, it examined application of fuzzy quality function development (QFD) for enabling leanness in a manufacturing organization [20]; and using fuzzy logic approach to leanness assessment [21].

So it seems that the meaning of leanness is interpreted in various ways by previous researchers [22, 23]. Therefore, the leanness level of a system can be defined and measured by comparing the current state with the worst case and the perfect case [4]. Thus, the level of leanness can be quantified. The benefit of a lean operation comes not from just reducing

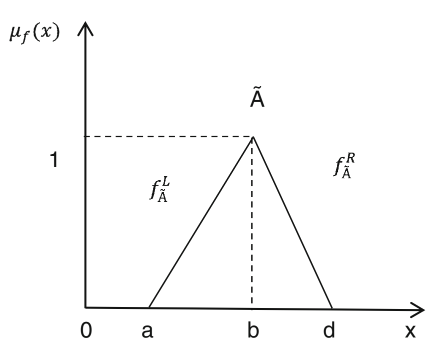

Fig. 4 Membership functions of triangular fuzzy numbers

waste, but from using less of everything compared with a company that is not lean. However, a number of operational benefits are available such as: shorter lead times, less cost for storage, and fewer defects shipped to customers [1, 24, 25]. So, leanness improves productivity, reduces costs, lead time, defects, and makes profitability much more viable [1]. Figure 1 shows a general schema of leanness. As shown in Fig. 1, the focus of this paper is Phase 4: identify lean attributes and their effects on the leanness level.

2.2 Metrics to leanness

Lean metrics are the performance measures that are used to track the effectiveness of lean implementation. Allen et al. [26] summarize a collection of lean metrics categorized in four major groups: *Productivity, Quality, Cost, and Safety.* Moreover, Seyed Hosseini et al. [27] have investigated the leanness criteria in auto part manufacturing using a Balance Scorecard approach. They have considered five different perspectives: financial, process, customer, employees, and suppliers; and extracted more than 50 criteria for being lean. Vinodh and Vimal [21] have proposed the 30-criteria leanness assessment model.

Dennis [28], in a proposed model to leanness considered shortest lead time, lowest cost, and the highest quality to the customer. Wan and Chen [9, 29] proposed a methodology to measure the overall leanness considering cost, time and value. This is supported by some authors (e.g. [30]), moreover they note that the application of lean tools reduces actual cost, removes defects as well as variation associated with defects, and improves product quality and value [30]. As a result, LM is able to manufacture products with less of every input, at lower costs, less development time and with a higher quality [31].

Slack [32] indexed customer value based on four attributes:

- Functional and performance (quality)
- Degree of excellence (level of defects)
- Time (lead time and development time)
- Costs for acquisition, developing, operating, and so on

Therefore, a benchmark for each lean metric or for the synthesized measure is needed if the level of leanness is measured using lean metrics to show the impact of each criterion on the leanness level.

In summary, cost, time, defects, and value are measures for leanness. The study does not follow the level of lean measurement in a company, but takes the role of the lean attributes (lead time, defects, cost, and value) to leanness. These attributes in the leanness process of manufacturing systems (door to door) are shown in Fig. 2.

According to Fig. 2 there are many processes in a manufacturing system. All of them somehow create

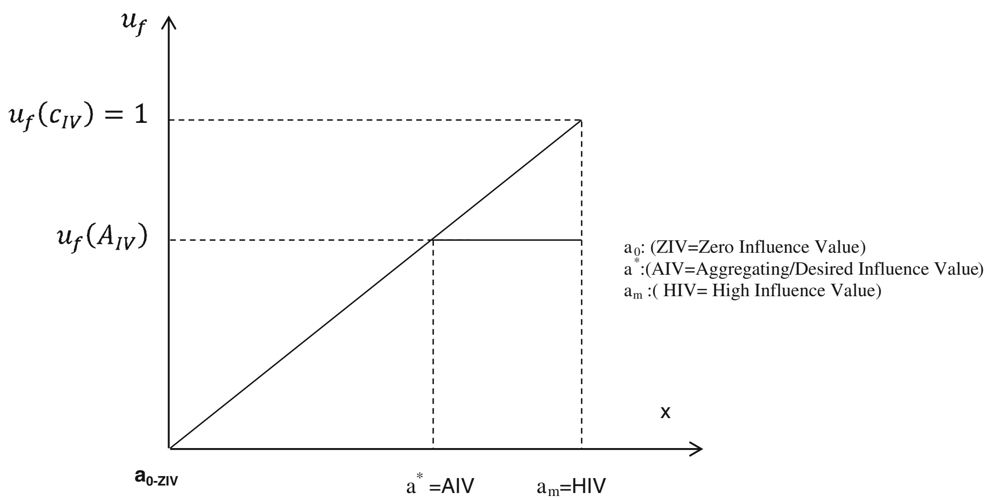

Fig. 5 Description of membership function by fuzzy set

value. This value is obtained through reduction in the lead time, cost and defects simultaneously or separately. The more reduction in these three items, the more value for the system is obtained. It does not matter how the factors are applied and in which steps the processes are affected through leanness of the manufacturing system, the result of all of them are increasing value of the finished goods.

3 Attributes to leanness

3.1 Lead time

The lean organization is flexible enough to provide a portfolio of products with mixed variability and short lead time to market [33], as well as shorter lead times to customer delivery [34]. One of the goals of a lean transformation is to drive down lead times to allow a company to respond quickly to its customers [2].

In fact, the total time that intervenes between the placement of an order and its receipt in clouds: processing time, transportation time, queue time, set-up time, and so on [35]. In other words, the total time for a work piece to flow through the system is represented as “production lead time” that can be used directly as the time variable [29]. Because leanness means developing a value stream to eliminate all waste, including time, and to ensure a level schedule [36], the unit of the time needs to be consistent with the value analysis time [2]. Consequently, lead time is the “key” measure of leanness. Short lead times and lead time reduction is such a basic tool in Lean that you will find it to be a strong measure of leanness [37, 38].

Table 1 A scheme of data in the proposed model

Metrics	ZIV/a_0		AIV/a^a		HIV/a_n
C_1	C_1 a_0	…	C_1 a^a	…	C_1 a_n
C_2	C_2 a_0	…	C_2 a^a	…	C_2 a_n
.	.	…	.	…	.
.	.	…	.	…	.
Cm	Cm a_0	…	Cm a^a	…	Cm a_n

3.2 Cost

The determination of the cost of a product by evaluating the use of resources in its manufacturing has always been a matter of great importance for companies [39]. Estimating the total costs of production process, new products, and technologies is a critical factor to survival and competitiveness of corporations. Hence, the average cost for a work piece to flow through the value stream should be calculated as the total cost [29].

Moreover, the overall program costs of adopting a new practice are a critical factor at each stage of decision-making: whether to adopt, to implement, and how to sustain a new practice [40]. The use of functional analysis based on costs and feedback from customers leads to an improved design and lower lifecycle costs to the customer [41]. As a result, an economic evaluation of companies needs formal tools for calculating how to weigh economic consequences of alternative courses of action [42].

3.3 Defects

Defects are products which do not match the desired design in properties and/or quality. Based on the degree of defects,

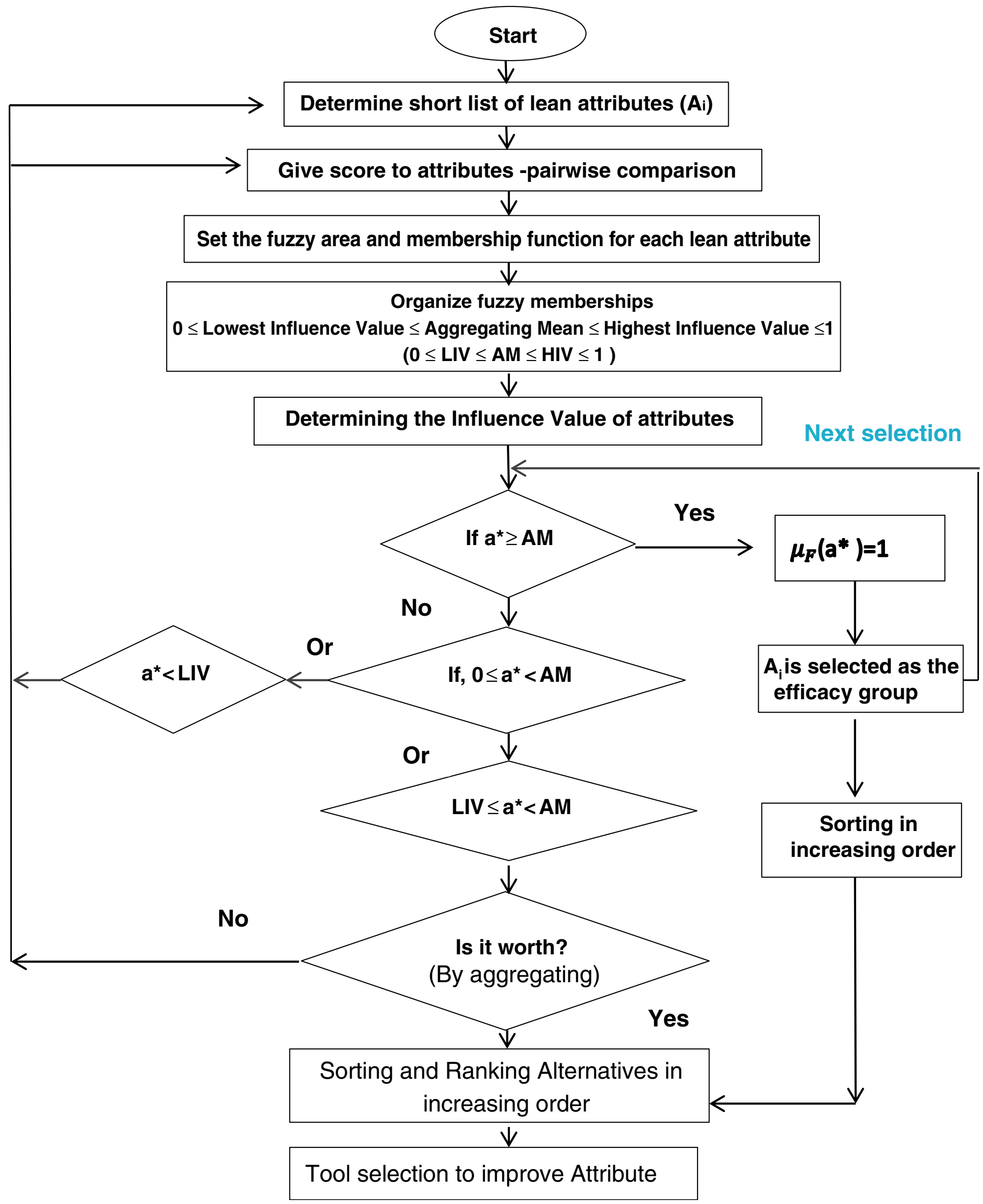

Fig. 6 Algorithm/proposed approach for identification of influence value of leanness attributes

the piece might be scrapped or need rework. Defects are caused due to inefficient processes, improper machine setting or machine breakdown, incorrect material or human error. The scope of defects encompasses generating scrap, rework or paperwork errors [43].

A defect refers to production that does not meet with the dimensional or quality standard in such a way that it can be rectified economically and is junked and sold for a disposal value. It represents loss of defective production, which cannot be finished. A defect can be made to realize some

Table 2 Numerical example with three metrics

Metrics	Point zero ZP/a_0	Point desired AP/a^a	Point maximum HP/a_n
C_1	0	50	80
C_2	0	55	80
C3	0	52	80

Table 3 Fuzzy membership values of lean attributes result: Example 1

metrics	ZP/a_0	AP/a^a	$U_f c_i$	HP/a_n
C_1	0	50	0.63	80
C_2	0	55	0.69	80
C3	0	52	0.65	80
Total			1.97	
$\sum_{i=1}^{4}\left(U_f c_i\right) = 1.97/3 = 0.66$				

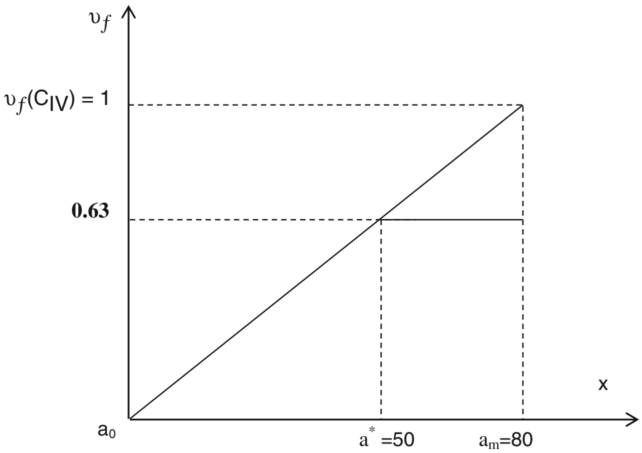

Fig. 7 Depiction of the membership performance of $C_{1:}$ numerical example

value after application of some more material, labor and so on. Cause of defect to a customer is poor quality goods [44]; poor quality that leads to a defect is never desirable.

This study will define such types of defects, which are detectable, undetectable, and not detected at a particular stage of production. In fact, hidden defects are those that are undetectable/not able to be detected at a particular stage of production [45].

1- The first type of defect is *internal scrap*. Internal scrap refers to defects produced in a company that have been caught by in-line or end-of-line inspection.
2- The second type of quality defect is what may be termed the *service* defect. Service defects are problems given to a customer that are not directly related to the goods themselves.
3- The third of these is the *product* defect. Products defects are defined here as defects in goods produced that are not caught by in-line or end-of-line inspections and are therefore passed on to customers [45].

In summary, the defects that create work and impede production efficiency [46], do not add value to the output [47]. Defects in the product normally lead to scrap, reworks, and customer dissatisfaction. Defects are things that have gone wrong with your products; quality characteristics which are not met [39]. Some authors (e.g., [48, 49]) consider defects as criteria in leanness. The application of lean tools can reduce actual cost, remove the defects as well as variation associated with defects, and improve product quality and value [30].

Table 4 Rating of four alternatives under four criteria

Alternative	Criteria			
	C_1	C_2	C_3	C_4
A_1	3	3	6	3
A_2	1	1	6	3
A_3	8	3	1	4
A_4	5	6	2	1

3.4 Value

Lean focuses upon meeting the needs of the ultimate user of the product. A requirement to correctly define which actions are values added and which are non-value-added is a clear description of which this ultimate customer is. Value needs to be defined in terms of customers' expectations of the product. This explanation can be broken down in dissimilar ways, but almost always includes as minimum features: product quality, delivery schedule, performance and meeting target cost [50].

In mathematical words, the output value can be calculated as the retail price multiplied by customer satisfaction rate (value=price×customer satisfaction), where the satisfaction rate should reflect the quality and functionality of the finished product, on-time delivery, and other factors that affect the customer's perception of the experience of purchasing this product [29]. The customer's perspective is that *value* is the key metric, those things the customer is willing to pay for [39] indicating that to improve the degree of leanness these criteria should be considered in operations.

4 Fuzzy logic and application within the maximum method

The fuzzy logic method has its basis in human logic that takes benefits from conceptual knowledge without limitations [18]. Some of the concepts of fuzzy logic include fuzzy sets, linguistic variables, probability distribution and fuzzy if–then rules. Most of the research in qualitative environment suffers from vagueness in which case data may not be expressed as exact numbers [51]. Linguistic assessment is recommended instead of numerical values [52]. The proper selection of linguistic variables is more important. The expressions of the experts need to be determined using fuzzy numbers and membership functions. To overcome the ambiguity associated with this assessment, triangular and trapezoidal membership functions are recommended [53]. These membership functions are used for transforming the linguistic variables into fuzzy numbers [54].

In fact, the theory of Fuzzy collections was formally presented for the first time by Zadeh [55] and developed by the founder of fuzzy logic [56]. From that time until now,

Table 5 Fuzzy membership values of lean attributes result: example 2

Criteria	Min	Mean	Max	$1[(a_{m}\text{-}a^{*})/(am-a_0)]$	Rank
A_1	1	3.5	6	$u_{F(a^*)}=1-[(6-3.5)/(6-1)]=0.50$	2
A_2	1	2.75	6	$u_{F(a^*)}=1-[(6-2.75)/(6-1)]=0.35$	4
A_3	1	4	8	$u_{F(a^*)}=1-[(8-4)/(8-1)]=0.43$	3
A_4	1	3.75	6	$u_{F(a^*)}=1-[(6-3.75)/(6-1)]=0.55$	1
		Total		1.8 3	
			$\sum_{i=1}^{4}(U_f c_i)=1.83/3=0.46$		
Methods		Prioritize			
Traditional		$A_3>A_4>A_1>A_2$			
New method		$A_4>A_1>A_3>A_2$			

it has been enhanced, considered very much and has had various submissions in different fields. There is no unique system of knowledge called fuzzy logic and there are a variety of methodologies proposing logical consideration of imperfect and vague knowledge [57].

A fuzzy set $\tilde{A}$ in this issue X is considered by a membership function $\mu_{\tilde{A}}(x)$, which acquaintances with each element x in A, a real number in the interval [0,1]. The function value $\mu_{\tilde{A}}(x)$ is labeled the grade of membership of x in $\tilde{A}$. Special cases of fuzzy numbers include crisp real number and intervals of real numbers. Although there are many forms of fuzzy numbers, the triangular and trapezoidal shapes are used most often for representing fuzzy numbers [58].

In decision analysis under the fuzzy environment, ranking fuzzy numbers is a very important decision-making procedure. Left–right (L–R) fuzzy number as the most general form of fuzzy number has been used extensively [59]. A key problem in operationalizing fuzzy set theory is how to equate fuzzy numbers. Various approaches have been developed for ranking fuzzy numbers [60–65]. Almost each approach, however, has pitfalls in some aspect, such as inconsistency with human intuition, indiscrimination, and difficulty of interpretation. So far, none of them is commonly accepted [65].

For the convenience of analysis, some basic concepts and definitions on fuzzy numbers are needed. They are stated as follows [66]. Let X be a universe set. A fuzzy subset A of X is defined with a membership function $\mu_{\tilde{A}}(x)$ that maps each element X in A to a real number in the interval [0,1]. The function value of $\mu_{\tilde{A}}(x)$ signifies the grade of membership of X in A. When $\mu_{\tilde{A}}(x)$ is large, its grade of membership of x in A is strong [65, 66].

Definition 1 A L–R fuzzy number $A=(m, n, \alpha, \beta)_{LR}$, $m\leq n$ and α, $\beta\geq 0$, is defined as follows [66]. Alternatively, a fuzzy number can also be generally expressed as:

$$u_{\underset{A}{\sim}}(x)=-\begin{bmatrix} L((m-x)/a), & -\infty<\times m, \\ 1, & m<\times<n, \\ R(x-n)/\beta), & m<\times<+\infty, \end{bmatrix} \quad (1)$$

which is referred to as L–R fuzzy number, denoted by $\widetilde{A}=(m,n,\alpha,\beta)_{LR}$, where $m\leq n$, $\alpha\geq 0$ and , $\beta\geq 0$ are respectively the left-hand and the right-hand spreads, and $L\left(\frac{m-x}{\alpha}\right)$, and $R\left(\frac{x-n}{\beta}\right)$, are continuous and non-increasing functions satisfying [65]. In other words, where α and β are the left-hand and the right-hand spreads, respectively. In the closed interval [m, n], the membership function is equal to 1. $L\left(\frac{m-x}{\alpha}\right)$, and $R\left(\frac{x-n}{\beta}\right)$, are non-increasing functions with L(0)=1 and R(0)=1, respectively. For convenience, they are, respectively, denoted as $\mu^{L}_{\underset{A}{\sim}}(x)$and $\mu^{R}_{\underset{A}{\sim}}(x)$. It needs to be pointed out that when $L\left(\frac{m-x}{\alpha}\right)$, and $R\left(\frac{x-n}{\beta}\right)$, are linear functions and $m<n$, fuzzy number A denotes a trapezoidal fuzzy number. When $L\left(\frac{m-x}{\alpha}\right)$, and $R\left(\frac{x-n}{\beta}\right)$, are linear functions and

Table 6 Test of example 2 based on new formula

Alternative	Min	Mean	Max	$(a_m-a^a)/(a^a-a_0)$	Rank
A_1	1	3.5	6	[(6−3.5)/(3.5−1)]=1	2
A_2	1	2.75	6	[(6−2.75)/(2.75−1)]=1.86	4
A_3	1	4	8	[(8−4)/(4−1)]=1.33	3
A_4	1	3.75	6	[(6−3.75)/(3.75−1)]=0.82	1

Table 7 Assessing six criteria with pairwise comparison

1	5	9	3	5	7
1/5	1	5	1/3	1/3	5
1/9	1/5	1	1/5	1/7	1/3
1/3	3	5	1	1	3
1/5	3	7	1	1	5
1/7	1/5	3	1/3	1/5	1

Table 8 Traditional weighted and ranking of Example 3

Criteria	Data analysis						Weight	Rank
C_1	1	5	9	3	5	7	0.45	1
C_2	0.2	1	5	0.333	0.333	5	0.11	4
C_3	0.111	0.2	1	0.2	0.2	0.333	0.03	6
C_4	0.333	3	5	1	1	3	0.17	3
C_5	0.2	3	7	1	1	5	0.19	2
C_6	0.143	0.2	3	0.333	0.333	1	0.05	5

$m=n$, fuzzy number A denotes a triangular fuzzy number. Let $\tilde{A}$ be a normal fuzzy number, whose membership function $\mu_{\tilde{A}}$ is defined as:

$$u_{\tilde{A}}(x) = -\begin{bmatrix} f_{\tilde{A}}^{L}(X), & a \leq \times \leq b \\ 1, & b \leq \times \leq c \\ f_{\tilde{A}}^{L}(X), & c \leq \times \leq d \\ 0, & otherwise \end{bmatrix} \quad (2)$$

where $F_{\tilde{A}}^{L} : [a, b]$ lead to [0,1], and $F_{\tilde{A}}^{R} : [b, c]$ lead to [0,1], and are two continuous mappings from the real line R to the closed interval [0,1]. The former is a strictly increasing function called left membership function and the latter is a monotonically decreasing function called right membership function (Fig. 3). In particular, when $b=c$, the trapezoidal fuzzy number is reduced to a triangular fuzzy number, denoted by $\widetilde{A} = (a, b, d)_{LR}$ so, triangular fuzzy numbers (Fig. 4) are special cases of trapezoidal fuzzy numbers.

According to Bojadziev and Bojadziev [57], triangular numbers are very often used in applications such as: fuzzy controllers, social sciences, managerial decision-making, and business and finance. More generally, the left and right branches of the triangular numbers (denoted by $A=(a, b, d)$, see Fig. 4) can be denoted correspondingly by $A^L = \left(a, \widetilde{A}, b\right)$ and $A^R = \left(b, \widetilde{A}, d\right)$. They will be considered triangular numbers and called corresponding left and right triangular numbers. The left triangular numbers A^L (Fig. 4) are suitable to represent positive larger or increasing, for instance big profit, high risk, and so on provided that b is a large number. The main objective in this study is to evaluate the impact of lean attributes on leanness, and identify the criteria in this process as well as prioritize the attributes. By this regard, we need to apply the left increasing model/positive larger to this problem.

Definition 2 For fuzzy set A, the support set of A is defined as follows [63]:

$$S(A) = \left\{X \in R | \mu_{\tilde{A}}(x) > 0\right\} \quad (3)$$

Moreover, the basic definitions of fuzzy sets theory are given [63].

Definition 3 A fuzzy set A is defined by a set of ordered pairs, a binary relation,

$$A = \{x, \mu_A(x) I \; x \in A, \mu_A(x) I \; x \in [0, 1]\} \quad (4)$$

where $\mu_A(x)$ is a function called membership function; $\mu_A(x)$ specifies the grade or degree to which any element X in A belongs to the fuzzy set A. This means with each element X in A, a real number $\mu_A(x)$ in the interval [0,1] which is assigned to X. Larger values $\mu_A(x)$ indicate higher degrees of membership.

Definition 4 A membership function of a triangular fuzzy number is defined by (5):

$$u_{F(X_i)} = \begin{pmatrix} 1 & if\; Xi \; \leq a \\ 1 - [(Xi - a)/(b - a)] & if\; a \leq Xi \prec b \\ 0 & if\; Xi \; \leq b \end{pmatrix} \quad (5)$$

Table 9 Fuzzy membership values of lean attributes result: example 3

Criteria	Min	Mean	Max	$1[(a_{m^-} a^*)/(am - a_0)]$	Rank
C_1	1	5	7	$u_{F(a^*)} = 1 - [(7 - 5)/(7 - 1)] = 0.67$	1
C_2	0.2	1.978	5	$u_{F(a^*)} = 1 - [(5 - 1.978)/(5 - 0.2)] = 0.37$	4
C_3	0.111	0.341	1	$u_{F(a^*)} = 1 - [(1 - 0.341)/(1 - 0.111)] = 0.26$	5
C_4	0.333	2.222	5	$u_{F(a^*)} = 1 - [(5 - 2.222)/(5 - 0.333)] = 0.40$	2
C_5	0.2	2.867	7	$u_{F(a^*)} = 1 - [(7 - 2.867)/(7 - 0.2)] = 0.39$	3
C_6	0.143	0.835	3	$u_{F(a^*)} = 1 - [(3 - 0.835)/(3 - 0.143)] = 0.24$	6

Table 10 Test of example 3 based on new formula

Criteria	Min	Mean	Max	$(a_m - a^a)/(a^a - a_0)$	Rank
C_1	1	5	7	(7−5)/(5−1)=0.5	1
C_2	0.2	1.978	5	(5−1.978)/(1.978−0.2)=1.699	4
C_3	0.111	0.341	1	(1−0.341)/(0.341−0.111)=2.865	5
C_4	0.333	2.222	5	(5−2.222)/(2.222−0.333)=1.471	2
C_5	0.2	2.867	7	(7−2.867)/(2.867−0.2)=1.549	3
C_6	0.143	0.835	3	(3−0.835)/(0.835−0.143)=3.128	6

5 Proposed method for measurement

In this section, a multi-attributes lean performance measurement model is proposed. The measurement model is applied in the following two steps:

1. Determine the main attributes to leanness.

Firstly, the lean attributes must be chosen based on the lean philosophy, which finally leads to the creation of more value for the end customers. In this study, lead time, cost, defects, and value are identified (literature review section) as the most important components to leanness.

2. Set the fuzzy area and membership function for each performance metrics.

To "fuzzify" the performance metrics (Ai) and develop the respective membership values, we use points "a_0" and "a_m", corresponding to the worst and best lean performance of each metric, respectively. Therefore, we consider the value of each metric using fuzzy membership functions (see Fig. 5). Triangular areas are formed to show the membership functions graphically.

Note: the aim of this research is to measure efficacy lean attributes on a leanness level. Indeed we want to know the influence value of attributes in leanness. There is several ways to introduce application functions [67]. The authors consider increasing/positive membership functions—the bigger the better—of the form. Hence, the fuzzy mathematic model $\left(u_{F(A_i)}\right)$ and graphic model change as below:

$$u_{F(A_i)} = \begin{pmatrix} 0 & if\ Xi\ \leq a \\ 1 - [(am - a^*)/(am - a0)] & if\ a \leq Xi \prec b \\ 1 & if\ Xi\ \leq b \end{pmatrix} \quad (6)$$

According to the graph in Fig. 5 and Table 1, if a criterion score is a_0 point [$\mu_f(ci)$=worst], the criteria is at a low level, a_m point stands for almost high/max level. The segment [u_f $(ci)=a_0$, a_m] of the vertical axis μ expresses the quantification of the degree of vagueness of its impacts on leanness.

As shown in Fig. 5, the high influence value for point "a_m" on the x-axis indicates the best performance for C_1, C_2, C_3, and C_4because the impact of all these metrics should be increased as much as possible. Hence, the fuzzy membership function value (μ_f) at point "a_m" is maximum and equal to one. Point "a_0" is the worst performance during each period. The setting of points "a_0" and "a_m" is arbitrary and they can be changed to a different value by the manufacturing system analyst.

So, for each performance metric, the fuzzy membership values can be calculated. Finally, the lean score is computed by taking the average of all membership values. This score can be easily used for lean performance evaluation, and give some directions for future improvement.

A scheme of the proposed model—Algorithm Developing Leanness Attributes within Fuzzy Approach—is plotted in Fig. 6.

Table 11 Comparison results between the two methods

Criteria	Traditional	New method
C_1	1	1
C_2	4	4
C_3	6	5
C_4	3	2
C_5	2	3
C_6	5	6
Traditional	$C_1>C_5>C_4>C_2>C_6>C_3$	
New method	$C_1>C_4>C_5>C_2>C_3>C_6$	

6 Numerical examples

A simple example is presented for better illustration of the proposed measurement method. Assume there are three items (C_1, C_2, C_3) impacting on the productivity of a company (Table 2). Some variables are defined based on: a_0, Zero Influences Value (ZIV); a^*, Aggregating/Desired Influences Value (AIV); a_m, sign of high influences value (HIV).

Table 12 Decision table on the experts' scores for attributes

	Lead time	Cost	Defects	Value
Lead time	(1, 1, 1, 1, 1)	(3, 3, 2, 4, 3)	(1/3, 1/2, 1/5, 1/3, 1/5)	(1/4, 1/2, 1/5, 1/3, 1/5)
Cost	(1/3, 1/3, 1/2, 1/4, 1/3)	(1, 1, 1, 1, 1)	(1/5, 1/2, 1/2, 1/4, 1/2)	(1/5, 1/3, 1/5, 1/4, 1/5)
Defects	(3, 2, 5, 3, 5)	(5, 2, 2, 4, 2)	(1, 1, 1, 1, 1)	(1/3, 1/3, 1/5, 1/2, 1/5)
Value	(4, 2, 5, 3, 5)	(5, 3, 5, 4, 5)	(3, 3, 5, 2, 5)	(1, 1, 1, 1, 1)

6.1 Example 1

Based on Eq. 6, the fuzzy membership values of all metrics are computed and shown in Table 3. For example $U_f c_1 = 1 - [(80 - 50)/\ (80 - 0)] = 0.63$. Other performance metrics can be calculated through the same procedure (see Table 3 and Fig. 7 (only for C_1)).

It should be noted that if membership values are equal to zero, it means they are out of the fuzzy area. Meanwhile, in this example all of the values are more than zero. By the way, the final score (66 out of 100) shows a satisfactory performance.

6.2 Example 2

Assume there is an evaluation matrix in respect of a goal (Table 4).

We assumed four projects (A_1–A_4), have different assessing criteria, the number of criteria being 4, respectively. Then we use the fuzzy membership values to gain the results, which are presented in Table 5.

6.2.1 Proposal of a new formula

Note: proposal of a formula for testing the result of new method with two steps:

- Calculate ranking test for all of the attributes
- Place in decreasing order

$$\begin{aligned}
&RT = Min\left(a_H - a^*\right)/\left(a^* - a_L\right)\\
&a_m = \text{Max/Highest expected values}\\
&a_L = \text{Min/Lowest expected values}\\
&a^* = \text{Ideal/aggregative expected values}\\
&RT = \text{Ranking Test}\\
&best\ choice = decreasing\ order: RT = Min\left(a_H - a^*\right)/\left(a^* - a_L\right)
\end{aligned} \tag{7}$$

Table 13 Fuzzy Evaluation Matrix with respect to the goal

	C1	C2	C3	C4
C1	(1, 1, 1)	(2, 3, 4)	(0.2, 0.26, 0.33)	(0.2, 0.3, 0.5)
C2	(0.25, 0.35, 0.50)	(1, 1, 1)	(0.20, 0.39, 0.50)	(0.20, 0.24, 0.33)
C3	(2, 3.6, 5)	(2, 3, 5)	(1, 1, 1)	(0.2, 0.31, 0.50)
C4	(2, 3.8, 5)	(3,4.4, 5)	(2, 3.6, 5)	(1, 1, 1)

According to this formula that ranks the alternatives based on decreasing order, the result will be the same as for example in the last matrix (Table 6).

6.3 Example 3

We assume project *A*, have different assessing criteria, the number of criteria being 6, respectively. The detailed weights and performance ratings (1-9) are presented in the matrix (Table 7).

Then, we use the traditional weighted and the above steps of new method to gain the results, which are presented in Tables 8, 9, 10, and 11.

7 Application of the new method

7.1 Multi-expert decision-making producer aggregations-practical example

Analysis of complex problems requires the efforts and opinions of many experts. Experts' opinions are expressed in words from a natural and professional language. These can be considered as linguistic values, hence described and handled by fuzzy sets and fuzzy logic [57]. Moreover, it is unlikely that expert opinions are identical. Usually they are either similar or conflicting to various degrees. They have to be combined or reconciled in order to produce one decision. We call this multi-expert decision-making producer aggregation; it is conflict resolution when the opinions are in conflict [57]. Therefore, in this study in addition to using experts' opinions, the aggregation is obtained by applying fuzzy averaging.

Table 14 Fuzzy Evaluation Matrix for the attributes

	Min	Mean	Max
C1	1+2+0.2+0.2	1+3+0.26+0.3	1+4+0.33+0.5
C2	0.25+1+0.2+0.2	0.35+1+0.39+0.24	0.5+1+0.5+0.33
C3	2+2+1+0.2	3.6+3+1+0.31	5+5+1+0.5
C4	2+3+2+1	3.8+4.4+3.6+1	5+5+5+1

Min minimum score devoted by experts, *Max* maximum score devoted by experts, *Mean* average score devoted by experts

Table 15 Final score of attributes

	Min	Mean	Max
C1	3.4	4.56	5.83
C2	1.65	1.98	2.33
C3	5.2	7.91	11.5
C4	8	12.8	16

Consequently, five experts' scores and weights have been measured in this study. The experts are the DMs who hold high knowledge and experience in lean. They are involved in the process of lean implementation practices. An average operation is used to aggregate the experts' valuation. Integrated presentation ratings and importance weights are shown in Table 12.

To fuzzy averaging consider n triangular numbers $A_i = \left(a_1^{(i)}, a_M^{(i)}, a_2^{(i)}\right), i = 1, \ldots, n$ using addition of triangular numbers and division by a real number.

$$A_{ave} = (A_1 + \ldots + A_n)/n$$
$$= \left[\left(a_1^{(i)}\right), \left(a_M^{(i)}\right), \left(a_2^{(i)}\right) + \ldots + \left(a_1^{(n)}\right), \left(a_M^{(n)}\right), \left(a_2^{(n)}\right)\right]/n$$
$$= \left[\sum_{i=1}^{n} a_1^{(i)}, \sum_{i=1}^{n} a_M^{(i)}, \sum_{i=1}^{n} a_2^{(i)}\right]/n$$

in which i is a triangular number,

$$A_{ave} = (m_1, m_M\, m_2) = \left(1/n \sum_{i=1}^{n} a_1^{(i)}, 1/n \sum_{i=1}^{n} a_M^{(i)}, \sum_{i=1}^{n} a_2^{(i)}\right) \quad (8)$$

7.2 Practical steps in new method

Step 1. Determining lean attributes

The lean attributes are: lead time, cost, defects, value (as explained in Sections 2 and 3).

Step 2. Pairwise comparison by five experts

Without assuming the interdependence between attributes, five experts are asked to evaluate all proposed attributes pairwise. They responded to questions such as "Which criterion impacts more on leanness, and how much more?" The responses were presented numerically and scaled on the basis of Saaty's 1–9 scale, where 1, represents indifference between the two criteria and 9 represents extreme preference for one criterion over the compared criterion. Each pair of criteria is judged only once.

Step 3. Organized viewpoints of experts in fuzzy approach

This step has been prepared based on "Eq. 7" and Tables 13, 14 and 15.

Step 4. Calculate fuzzy membership values and their arithmetic mean scores.

For each metric, the fuzzy membership values are calculated. The lean score is computed by taking the average of all membership values. This score can be easily used for the evaluation of the efficacy/influence value of lean attributes on leanness, and can give some directions for future improvement. It should be noted that this new method can be used in various conditions and with different variables.

Condition1 In this case, data is obtained from Table 15; as shown in Table 16.

Condition 2 Based on this condition there are three groups' data: the lowest/worst and the highest/desired performance (determined by experts); and average score is the mean of rating. Based on Eq. 6, the fuzzy membership values of all metrics are computed as shown in Table 17.

Point a_0 is the lowest/worst performance; point a* is the aggregating/desired score of Table 17, point a_m, is the maximum that is determined as the ideal point (it is arbitrary). According to Eq. 6, we can calculate fuzzy membership values as well as their arithmetic scores. It should be mentioned that the weights for all performance (IV) metrics in this study are the same, but they can be individually different depending on their importance.

The performance (IV) data of C_1 and C_2 are less than 50 %. They have low membership values (0.35, 0.15). However, the C_3 score is more than half (0.61=61 out of 1 (0)), and finally, the C_4 score (0.98=98 out of 1(0)) has achieved the best performance (IV) among all performance metrics. Noticeably, the final lean score (52 out of 1(0)) shows a satisfactory performance (IV).

Table 16 Fuzzy membership values of lean attributes result

Metrics	Min	Mean	Max	$1[(a_m - a^*)/(am - a_0)]$	Rank
C1	3.4	4.56	5.83	$u_{F(a^*)} = 1 - [(5.83 - 4.56)/(5.83 - 3.4)] = 0.48$	3
C2	1.65	1.98	2.33	$u_{F(a^*)} = 1 - [(2.33 - 1.98)/(2.33 - 1.65)] = 0.49$	2
C3	5.2	7.91	11.5	$u_{F(a^*)} = 1 - [(11.5 - 7.91)/(11.5 - 5.2)] = 0.43$	4
C4	8	12.8	16	$u_{F(a^*)} = 1 - [(16 - 12.8)/(16 - 8)] = 0.60$	1
Results			New method$C_4>C_2>C_1>C_3$ Traditional$C_4>C_3>C_1>C_2$	$\sum_{i=1}^{4} \left(U_f c_i\right) = 2/4 = .0.50$	

Table 17 Fuzzy membership values of lean attributes result

Metrics	a_0	a^a	a_m		Rank
C1	0	4.56	13	$u_{F(a^*)} = 1 - [(13 - 4.56)/(13 - 0)] = 0.35$	3
C2	0	1.98	13	$u_{F(a^*)} = 1 - [(13 - 1.98)/(13 - 0)] = 0.15$	4
C3	0	7.91	13	$u_{F(a^*)} = 1 - [(13 - 7.91)/(13 - 0)] = 0.61$	2
C4	0	12.8	13	$u_{F(a^*)} = 1 - [(13 - 12.8)/(13 - 0)] = 0.98$	1
Lean score	$\sum_{i=1}^{4} (U_f c_i) = 2.09/4 = 0.52$				

Based on the results, even though the attributes IV is more than half it should be developed in order to increase its lean IV level. Moreover, other performance/IV metrics can be added through the same procedure.

Condition 3 In this circumstance, comprehensive data and results are considered. The lowest point is named ZIV; similarly, maximum point is named HIV. The basis of this range (best and worst points) is voluntary; similarly, we can set other points arbitrarily so that they can be changed to a different value by an analyst. By the way, in this instance a_0 is considered to be the lowest level for all desired points.

The membership function for each performance metric is obtained as follows (Table 18 and Fig. 8): $u_{F(a^*)} = 1 - [(4.56 - 0)/(5.83 - 0) = 0.78$ (only for C1).

Finally, we ranked the four mentioned alternatives in three methods (Table 19).

Based on Tables 16, 17, and 18 in general, and Table 18 and Fig. 8 in particular, the fuzzy membership values of all metrics are computed and the three results are:

1- The third attribute is related to defects that were added to other metrics. The minimum expected impact of defects on leanness is 45 % and the aggregating score is 69 %. It is indicated that defects are a significant factor of leanness.
2- Minimum expected average of impact of whole attributes on leanness is 56 % and the aggregating score is 78 %.
3- According to findings of this research, within fuzzy approaches (using of multi-expert decision-making and fuzzy averaging) the ranking of attributes on leanness are: cost>value>lead time>defects.

So, in this study, lean metrics as leanness attributes increased from three to four. So that in addition to lead time, cost, value; the defect metric can be considered as a quantitative metric to leanness. Using fuzzy membership values, this study has presented the steps of a measurement method to measure the efficacy of lean attributes of manufacturing systems.

8 Discussion and conclusion

In order to increase competitive advantage, many companies consider that a well designed and implemented LM system is an important approach. Under this condition, building on the closeness and long-term relationships between criteria and techniques is a critical success factor to establish the system. Therefore, the tools selection problem becomes the most important issue to implement a successful LM system.

In general, lean makers attribute problems because they adhere to uncertain and imprecise data, but fuzzy set theory is adequate to deal with them. This paper presents a new approach for ranking L-fuzzy numbers. Using fuzzy membership values, this study has presented the steps of a

Table 18 Comprehensive results of influence values of lean attributes

1 Metrics	2 ZIV/a_0	3 ($U_f a_0$)	4 Min LIV/a_1	5 ($U_f a_1$)	6 Mean AIV/a^a	7 ($U_f a*$)	8 Max HIV/a_2	9 ($U_f a_2$)
C1	0	0	3.4	0.58	4.56	0.78	5.83	1
C2	0	0	1.65	0.71	1.98	0.85	2.33	1
C3	0	0	5.2	0.45	7.91	0.69	11.5	1
C4	0	0	8	0.50	12.8	0.80	16	1
Lean score	$\sum_{i=1}^{4} (U_f c_i) = 0/4 = 0$		$\sum_{i=1}^{4} (U_f c_i) = 2.54/4 = 0.56$		$\sum_{i=1}^{4} (U_f c_i) = 3.12/4 = 0.78$		$\sum_{i=1}^{4} (U_f c_i) = 4/4 = 1$	

Column 2 (ZIV/a_0) all of the scores (C_1–C_4) equal zero (0)

Column 4 (LIV/a_1) minimum scores are devoted (C_1–C_4) by experts

Column 6 (AIV/a^a) aggregating scores are devoted (C_1–C_4) by experts

Column 8 (HIV/a_2) maximum scores are devoted (C_1–C_4) by experts

Table 19 Comparison between ranking methods

	Fuzzy	New method	Traditional
Lead time	4	3	3
Cost	1	1	4
Defects	3	4	2
Value	2	2	1

method to measure the value of influences on the leanness of manufacturing systems. Lead time, cost, defects, and value were identified as the most important components to leanness. These items are emphasized by so many authors, for example, lead time and cost [31, 67]; defects [48, 49]; and value [29, 39]. So these metrics can be useful criteria for the assessment of the application of lean tools and techniques [40].

In this paper, we have developed a positive ranking approach for fuzzy numbers by introducing a positive ideal point. This ranking approach considers not only the increasing/positive value, but also the DM's attitude towards risks, which has rarely been considered in existing fuzzy ranking approaches. It has been shown that the proposed increasing ranking approach has very strong discrimination power and can compare and rank fuzzy numbers that are unable to be ranked by the maximizing set and minimizing set method. In comparison with those approaches that do not consider the DM's attitude towards risks, the proposed positive ranking approach is more flexible and more practical.

In addition, this study provides a method to evaluate the role of lean attributes on leanness and leanness requires selection of the best tools and techniques to ensure continuous improvement. Furthermore, from a dynamic sense, the influence value of attributes on the leanness of all periods can be recorded and benchmarked based on a timely period. Hence, the lean performance trend of each period can be analyzed and irregular performance or unsatisfactory progress can be revealed clearly. This information can also help managers and DMs to find and diagnose the problems in their processes.

The proposed model is able to measure both qualitative and quantitative measures. Furthermore, it can measure different measures with different units (e.g. cost and time) and bring them together into a single unit-less score and it includes all efficacy and performance features.

According to the proposed model, we can determine not only the status of all possible attributes but also the ranking in increasing order. Significantly, the proposed method

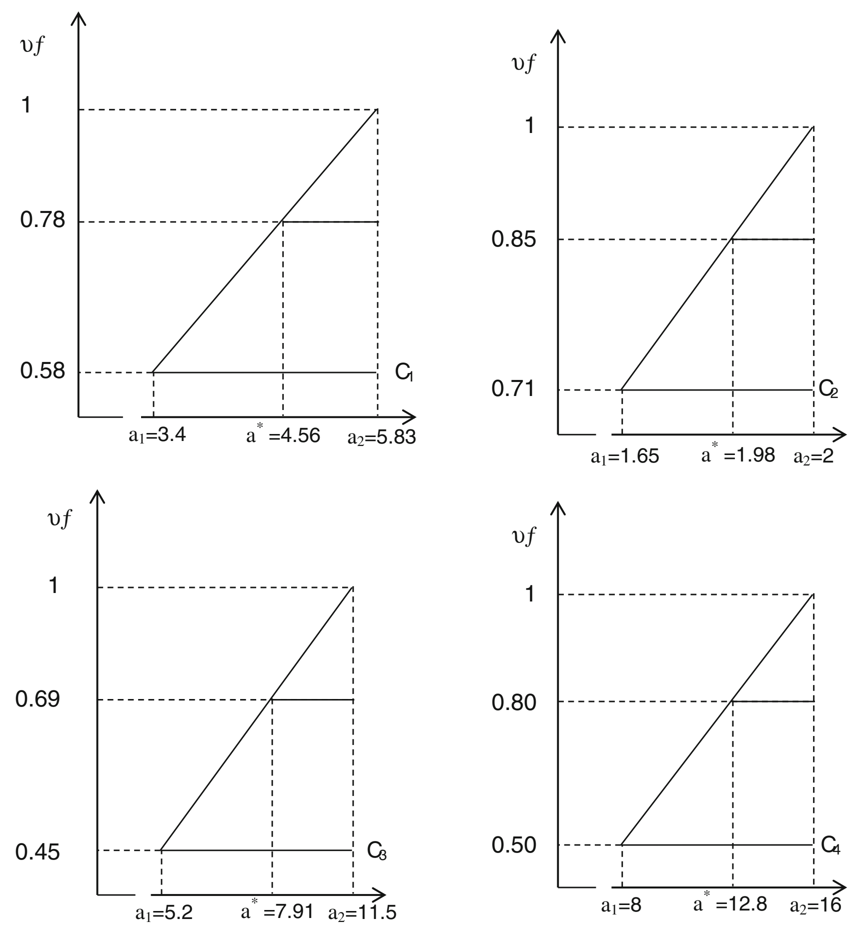

Fig. 8 Plotting the membership functions for lean attributes

provides more objective information for the selection and evaluation of lean tools in a leanness system. The systematic framework for the assessment of attributes in a fuzzy environment presented in this paper can be easily extended to the analysis of other management decision problems.

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