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A leanness assessment methodology based on neutrosophic DEMATEL

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ABSTRACT

Lean systems which provide the elimination of waste and increase productivity in both manufacturing and service systems are highly desired by the companies. Designing a lean system requires enormous amount of efforts and is time consuming unless the right steps are followed. The first step of lean implementation is the assessment of leanness which determines the status quo of the existing system with respect to leanness. In searching of a comprehensive evaluation method, this study aims to propose a leanness assessment methodology which is able to aid company's lean transformation. This study mainly differs from the existing studies by taking into account a wide range of lean indicators with a comprehensively designed questionnaire and evaluating leanness via neutrosophic DEMATEL (The Decision Making Trial and Evaluation Laboratory) based scoring structure. The proposed methodology is applied in three companies. Moreover, sensitivity analysis concerning metrics and comparison with classic DEMATEL are performed.

1. Introduction

Lean production is a performance improvement philosophy whose main objective is to eliminate waste throughout a system. It has its roots in the Toyota Production System (TPS) and has been applied successfully in diverse sectors since then. In general, lean production is based on a set of philosophies and principles from both management and application perspectives. Organizations adopting lean as a philosophy has shown improved financial and operational performance [1].

From an application perspective, lean tools which are systematic waste identification, waste elimination, and process improvement aids, should be applied to improve the leanness index of a company. For successful lean implementation Bhasin [1] and Basin & Burcher [2] emphasize the importance of adopting continuous improvement, cellular manufacturing, one-piece flow, Single Minute Exchange of Dies (SMED), 5S, Kanban, Total Productive Maintenance (TPM), Jidoka and Process Mapping lean tools. The advantages of lean principles and lean tools such as cellular manufacturing have been shown in the literature [3,4].

From a management perspective, Just in Time (JIT) philosophy focuses on the efficient utilization of resources in a system. To achieve efficiency; small-lot manufacturing with minimal buffers as well as active and quick feedback mechanisms are the cornerstones of leanness [5]. The application perspective that reinforces the adoption of small-lot manufacturing is based on continuous improvement which is called "kaizen" principle. Kaizen empowers operator to search, analyze, and provide solutions for abnormalities and quality problems. To encourage operator implementing kaizen, human resources policies that are in relation to motivation and commitment should also be adopted. To ensure this adoption, teamwork, job rotation, and training should be accentuated in the worker selection process [6]. Management, application perspectives, and human resources policies should be considered for lean transformation. Lean transformation is regarded as a necessity to grow and stay competitive in the market [1]. Lean transformation is a tedious process that should be carefully managed. Prior to this complex transformation process, a leanness assessment, which is the main aim of this study should be performed. Understanding company's current leanness level gives rise to drawing a road map to a lean journey.

The objective of this study is to propose a methodology that systematically measures leanness from management and application perspectives and point out the improvement opportunities throughout organizations on their lean journey. Unlike other studies' leanness assessment approaches, this study covers a large scope of metrics and evaluating leanness via neutrosophic DEMATEL based scoring structure. A questionnaire is designed specifically for evaluating lean metrics. Moreover, the proposed methodology is realized in three companies.

The remainder of this paper is mapped as follows. Section 2 provides the relevant literature with respect to lean metrics and leanness assessment methods. Section 3 explains the proposed methodology by disintegrating into three parts. In the first part, lean metrics are

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presented by breaking down to particular sub-metrics. In the second part, the proposed technique; neutrosophic DEMATEL is explained and in the third part, information about the questionnaire and scoring method are provided. Section 4 includes the application of the proposed methodology. Section 5 includes results and discussion including sensitivity analysis, comparison with classic DEMATEL, and representativeness & limitations of the proposed methodology. Finally, the conclusion of the study is presented in Section 6. Moreover, the literature review summary table, questionnaire prepared for leanness assessment, expert consideration tables, and sensitivity analysis with respect to each metric are given in the Appendix.

2. Literature review

Reviewed lean implementation frameworks in the literature indicate leanness assessment as a first step on the lean journey of organizations [7,8]. The focus of leanness assessment is to identify an organization's current level of lean adaptation. The first attempt of leanness assessment dates to the end of the 20th century and is documented by Moore & Gibbons [9], Karlsson & Ahlström [10], Panizzola [11] and they commonly aimed at identifying leanness level accurately while pointing out their weak sides which need improvement. Identification of leanness level gives rise to maintaining the strong sides and improving the weak sides on lean implementation.

Although there are numerous leanness assessment studies in the literature, the need for a systematic model still exists. A systematic assessment method, upon application, ideally would help the organizations to identify their leanness level.

Leanness assessment is based on two steps in general. The first step is to identify the lean indicators while the second step is method adoption. Considering this two-step process, literature is reviewed in two categories, i.e lean metrics, and leanness assessment methods. Moreover, a comprehensive literature review table is provided in Appendix Table A1.

2.1. Lean metrics in the literature

The first step in developing a leanness assessment methodology is to identify lean metrics [34]. The success of leanness assessment is heavily based on the scope of metrics and indicators to evaluate these metrics. After reviewing more than fifty papers on leanness assessment, various metrics and indicators surfaced in the literature, such as "first time through", "on time shipment ratio", "WIP level", "existence of a continuous improvement culture", "total space for storage" and "material handling", and others. Further, a nested structure between metrics is observed. For instance, WIP level indicator is employed to assess quality, delivery, material handling, and lead time metrics in different studies [12–15]. Another observation is worth mentioning about the wording of metrics, terms such as inventory management and inventory control resemble in definition, so these metrics are represented under the one term, in this case, inventory control (see Table A1). After proper arrangement, a total of 42 different metrics are defined in the literature. Quality is the most considered metric in the majority of assessment studies following flexibility, JIT/continuous flow, continuous improvement, and multifunctional teams. The earliest studies on leanness assessment generally focus on JIT/continuous flow, continuous improvement, multifunctional teams, supplier & customer relationships, employee empowerment [9–11], flexibility, and quality [9]. Furthermore, application of cellular manufacturing and cost were emerging metrics in years 2011–2015 [7,16–28]. In more recent years, labor productivity improvement, time effectiveness, and delivery metrics draw increasing attention [29–32].

Metrics that are associated with management practices, including commitment, strategic planning, culture improvement, leadership, information sharing/technologies, and environmental technologies were considered in the years 2016 and 2017 [12,33–36]. However, visual management, and new product development - the most important aspects of lean philosophy- become the least investigated metrics on leanness assessment studies in the current literature [30,37–40].

Table 1
Categories of main and sub-metrics.

PERFORMANCE	PROCESS	INVENTORY
Dock-to-Dock Days	One Piece Flow	Supermarket
First Time Through	Layout/Handling	Lot Size Reduction
On Time Shipment	Standardization	Pull Control System
Floor Space	Kaizen	Inventory Turnover
Sales per Person	Visual Management	
Average Cost per Unit		
SUPPLIER	**HUMAN RESOURCES MANAGEMENT**	
JIT Delivery	Management Commitment	
Supplier Involvement	Capability Development	
High Quality	Multifunctional Teams	
Kaizen Culture	Team Works	
	Employee Empowerment and Involvement	

After carefully investigating the scope of metrics in the literature, 5 main metrics are defined, i.e. Performance, Process, Inventory, Supplier, and Human Resources. These main metrics are then divided into several measurable/assessable sub-metrics (See Table 1). To the best of the authors' knowledge, this study is the first attempt considering such a large scope of metrics, ranging from management to application perspectives.

2.2. Leanness assessment methods in the literature

The second stage of developing a leanness assessment model, after identifying the leanness metrics, is to choose a suitable method to evaluate these selected metrics. Drawing on the current literature, "survey" stands out to be the most preferred method. Studies that used a questionnaire survey method intend to ignore lean being a philosophy from a multi-dimensional perspective in terms of assessing organization leanness. For instance, Karlsson & Ahlström [10], Galankashi et al. [13], Soriano-Meier & Forrester [41] evaluated leanness from an operational perspective while Gonçalves & Salonitis [14] considered leanness from an assembly line design perspective. Similarly, Ihezie & Hargrove [42] considered manufacturing-related assessment while Welo & Ringen [33] assessed product development leanness. On the other hand, Perez & Sanchez [43] incorporated technology management and flexibility perspectives and Sezen et al. [23] considered internal operational factors such as POKA YOKE, one-piece flow, set-up time reduction. In conclusion, studies incorporating a multi-perspective viewpoint either underestimated the relative importance of factors [21,44] or considered factors from a limited direction [39]. Hence, the findings from the analysis point out a need for a multi-perspective and in-depth assessment tool.

Fuzzy logic which facilitates decision making in ambiguous environments was also adopted for leanness assessment in service and manufacturing sectors [22,45,46] either via assigning fuzzy importance weights to criteria [47] or by providing integrations with multi criteria decision making (MCDM) techniques such as MULTIMOORA [48]. Furthermore, fuzzy logic was also employed to choose appropriate lean strategies for deployment [49] and to model the vagueness in human judgments [28]. AHP, ANP, and DEMATEL are some of the MCDM techniques for leanness assessment, too. AHP, ANP, and DEMATEL were utilized either as a sole technique to find a single lean performance score (LPS) as seen in the studies of DeWayne [16] and Wong et al. [27] or as a complementary scenario to determine the best move directions on the lean journey [7] Furthermore, TOPSIS was employed to evaluate the lean transformation stage of enterprises via a focus group consisting of advisors, experts, and academicians [50].

In addition to fuzzy logic, other methods such as simulation [15], benchmarking [51], variability source mapping [52], dynamic modeling [53], and structural equation modeling [29] to assess leanness are

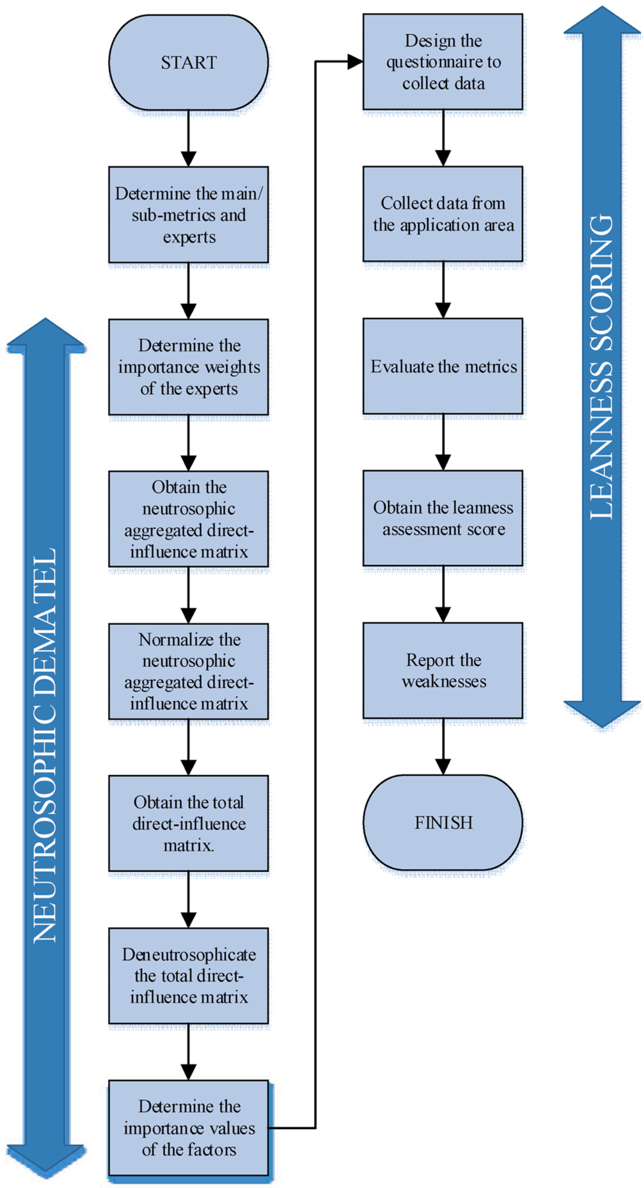


Fig. 1. Flow chart of the proposed methodology.

observed. Of all the aforementioned, the top five lean assessment methods are questionnaire-based analysis, fuzzy logic, AHP&ANP, simulation, and benchmarking.

It is evident that methods that underestimate the vagueness of information would result failure to evaluate a phenomenon that includes human judgment. To handle this situation fuzzy logic is a widely utilized methodology. However, in recent years, studies [54,55] showed the inability of fuzzy logic to deal with non-membership and indeterminacy. To deal with this situation, this study aims, by utilizing neutrosophic DEMATEL, to assess the leanness level of an organization from a broad perspective. Broad perspective not only considers membership but also regards truthiness, indeterminacy, and falsity which represent reality effectively [57]. Based on the previous studies, there lacks a methodology utilizing neutrosophic DEMATEL for the assessment of leanness. In addition to the developed leanness assessment questionnaire, another key contribution of this study to the literature is the demonstration of the use of neutrosophic DEMATEL in leanness assessment for the first time.

3. The proposed methodology

Methodology for this study is based on a comprehensive literature review with respect to lean metrics and techniques, and interviews with lean experts from the manufacturing sector and academics. The first step is to identify main and sub-metrics and categorize them. Categorization, which presents an original structure, is also one of the novelties this study offers. It is clear that not all leanness metrics have the same importance level to an organization. To clarify the relationship and their importance weights, neutrosophic DEMATEL, which will be elaborated in the next sections, is utilized for the purpose of leanness assessment.

To collect data, a questionnaire which can be seen in Appendix Table B1, is designed and sent to companies where the assessment is performed. The questionnaire includes 71 questions with various scales. After data are gathered via questionnaire, the metrics are then evaluated and the leanness assessment score is obtained. This evaluation exposes the weaknesses of organizations in terms of being a lean enterprise. Fig. 1 represents all steps of the proposed methodology.

3.1. *Lean metrics*

Lean metrics are identified based on literature review and interviews with experts in the field. The most frequently used metrics are defined and under 5 different categories including performance, process, inventory, supplier, and human resources management. Table 1 represents these 5 main metrics and their sub-metrics.

3.2. *The technique used in the proposed methodology*

The interactive nature of lean metrics requires the evaluation method to be able to evaluate the effect of lean metrics among each other and find importance weights. Neutrosophic DEMATEL is chosen because of its ability to determine the effects among metrics.

Another reason for using neutrosophic DEMATEL is because of its comprehensive structure of the neutrosophic sets that it utilizes. Unlike the classical fuzzy sets which only consider membership functions and become insufficient to deal with indeterminacy, neutrosophic sets are accepted to represent real-world cases effectively and efficiently by incorporating all dimensions of decision-making environment via truth, indeterminacy, and falsity membership functions [55]. The neutrosophic approach was introduced to the literature by Smarandache [56] in 1999 and it has been used in various applications since then. In 2018, neutrosophic DEMATEL was introduced by Abdel-Basset et al. [55] and has few applications such as project selection [54], determining the effect of IoT on supply chain [53], investigating the factors of coastal erosion [58] and evaluation of municipalities concerning environmental sustainability [59].

3.2.1. *Neutrosophic DEMATEL*

DEMATEL method was developed by the Science and Human Affairs Program of the Battelle Memorial Institute of Geneva between 1972 and 1976. This method was used for researching and solving the complex and intertwined groups of problems [60]. There are various applications of DEMATEL including evaluation of green suppliers [61], prioritization of investment projects [62], evaluation of internal hospital supply chain performance [63], industry sector impact analysis on the composition of the business ecosystems [64], the impact of big data analytics capabilities on organization performance [65], and so on.

This methodology can verify the interdependence among the attributes/criteria, and the result demonstrates a visual diagram of the relationships between the criteria, which is referred to as the direct relationship map. However, the classical DEMATEL fails to take the vague and imprecise decision-making environment into account and is also incapable of dealing with indeterminacy. Hence, DEMATEL model is modified and after fuzzy versions, in the latest applications, synthesized with neutrosophy. The advantages of neutrosophic approach to the DEMATEL are listed as follows [55]:

- Unknown information can be presented by utilizing an indeterminacy degree. Hence, considerations of the experts about the unsure preferences can easily be provided.
- Disagreement among the decision-makers and experts can easily be indicated.
- All parts of the decision-making environment can be managed by determining truthiness, indeterminacy, and falsity.

In this study, the neutrosophic DEMATEL method is used to obtain the importance weights of the main lean metrics. Afterward, the obtained importance weights are used in the leanness scoring system.

Before providing the steps of neutrosophic DEMATEL method, preliminaries are provided as follows by considering the studies of Abdel-Basset et al. [55] and Awang et al. [58].

Preliminaries

Definition 1

Let X be a space of points including generic elements represented by x. Then a neutrosophic set Q in the space X is defined as $Q = \{\langle x,\ T_Q(x), I_Q(x), F_Q(x) > \ x \in X\}$

Different from the membership function which is the essence of classic fuzzy sets, three parameters are used in the representation of neutrosophic sets. Within the set, $T_Q(x)$ corresponds to a truth-membership function, $I_Q(x)$ is the indeterminacy-membership function, and lastly, $F_Q(x)$ is the falsity-membership function. All the functions are real standard subsets of $]0^-, 1^+[$, Hence, the sum of $T_Q(x),\ I_Q(x)\ and\ F_Q(x)$ is $0^- \le supT_Q(x) + supI_Q(x) + supF_Q(x) \le 3^+$.

Definition 2

Single valued neutrosophic set is considered as the generalized form of classic, fuzzy, and intuitionistic fuzzy sets. Since it is difficult to use nonstandard subsets in real-life cases, single-valued neutrosophic numbers (SVNNs) which were proposed by Wang et al. [66], are utilized. There exist basic properties of set-theoretic operators defined within single-valued neutrosophic sets [66]. Hence, the sum of $T_Q(x)$, $I_Q(x)\ and\ F_Q(x)$ satisfies the condition $0 \le T_Q(x) + I_Q(x) + F_Q(x) \le 3$.

Definition 3

In most of the decision-making problems, decision-makers have different importance values depending on their expertise and positions. Hence, it is required to determine the importance weight of each decision-maker. If SVNNs are used for the rating of decision-makers, mth decision maker's weight can be stated as in Eq. 1.

Table 2
Abbreviations and symbols used in N-DEMATEL method.

Abbreviation/ Symbol	Definition
SVNN	Single Valued Neutrosophic Number
$T_Q(x)$	Truth-membership function
$I_Q(x)$	Indeterminacy-membership function
$F_Q(x)$	Falsity-membership function
$<T_{ij}, I_{ij}, F_{ij}>$	The degree of influence that the factor i has on the factor j including truthiness, indeterminacy and falsity values, respectively
w_m	The importance weight of decision-maker "m"
$A^{(m)}$	mth decision maker's decision matrix
A	Aggregated decision matrix
a_{ij}	Influence value of factor i on factor j in the aggregated decision matrix
X_Q	Deneutrosophicated value of neutrosophic number Q
A^G	Neutrosophic aggregated direct-influence matrix
k	A parameter used in the normalization process
B	Neutrosophic normalized aggregated direct-influence matrix
S	Total direct-influence matrix
s_{ij}	Influence value of factor i on factor j in the total direct-influence matrix
B_T	Matrix consisting of only truthiness values in B
B_I	Matrix consisting of only indeterminacy values in B
B_F	Matrix consisting of only falsity values in B
T_{ij}	Truthiness value of factor i on factor j
I_{ij}	Indeterminacy value of factor i on factor j
F_{ij}	Falsity value of factor i on factor j
S'	Deneutrosophicated total direct-influence matrix
s'_{ij}	Influence value of factor i on factor j in the deneutrosophicated total direct-influence matrix
a_i	Sum of row i in the deneutrosophicated total direct-influence matrix
b_j	Sum of column j in the deneutrosophicated total direct-influence matrix

$$w_m = \frac{1 - \sqrt{\left\{(1 - T_m)^2 + (I_m)^2 + (F_m)^2\right\}/3}}{\sum_{m=1}^{p}\left(1 - \sqrt{\left\{(1 - T_m)^2 + (I_m)^2 + (F_m)^2\right\}/3}\right)} \tag{1}$$

Definition 4

The judgments about the factors (Depending on the scope of the study, factors can be criteria or metrics like in this study) in an MCDM problem can be performed differently by each decision-maker. However, it is needed to merge these individual judgments within the steps of the technique. Hence, considering this case, Let $A^{(m)} = (a_{ij}^m)_{n*n}$ be the mth decision maker's decision matrix and $w = (w_1, w_2, \ldots, w_p)^T$ be the importance weight vector of the decision-makers. Then, the judgments of various decision-makers having different importance weights can be aggregated as in Eq. 2.

Table 3
Linguistic variables and their corresponding single-valued neutrosophic numbers.

Linguistic Variable	SVNN
Very Unimportant (VU)	(0.1, 0.8, 0.9)
Unimportant (U)	(0.35, 0.6, 0.7)
Medium Important (MI)	(0.5, 0.4, 0.45)
Important (I)	(0.8, 0.2, 0.15)
Absolutely Important (AI)	(0.9, 0.1, 0.1)

$$A = (a_{ij})_{n*n}$$
$$a_{ij} = SVNWA_w\left(a_{ij}^{(1)}, a_{ij}^{(2)}, \ldots, a_{ij}^{(p)}\right)$$
$$= w_1 a_{ij}^{(1)} \oplus w_2 a_{ij}^{(2)} \oplus \ldots \oplus w_p a_{ij}^{(p)} \quad (2)$$
$$= \langle 1 - \prod_{m=1}^{p}\left(1 - T_{ij}^{(m)}\right)^{w_m}, \prod_{m=1}^{p}\left(I_{ij}^{(m)}\right)^{w_m}, \prod_{m=1}^{p}\left(F_{ij}^{(m)}\right)^{w_m}\rangle$$

Definition 5

Similar to the defuzzification process which is utilized as the last step to obtain crisp numbers in the classic fuzzy methodologies. Deneutrosophication can be defined as obtaining crisp real numbers from neutrosophic numbers. Let $Q = \{\langle x, T_Q(x), I_Q(x), F_Q(x) > x \in X\}$ be an SVNN and the corresponding crisp real number is X_Q can be computed as in Eq. 3.

$$X_Q = 1 - \sqrt{\left\{(1 - T_Q(x))^2 + (I_Q(x))^2 + (F_Q(x))^2\right\}/3} \quad (3)$$

After providing the basic definitions, all the abbreviations and symbols used within N-DEMATEL are provided within Table 2 to enhance the clarity of the steps. Afterward, the steps of neutrosophic DEMATEL are provided [58].

Step 1: Obtain A^G which is the neutrosophic aggregated direct-influence matrix

The considerations of each expert about the influence of one factor on the other factor are collected via the scale provided in Table 3.

After the importance weights of experts are obtained via Eq. 1, they are aggregated via Eq. 2 and the aggregated direct-influence matrix, A^G is obtained as below.

$$A^G = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{bmatrix}$$

In the matrix, a_{ij} which is an SVNN in the form of $< T_{ij}, I_{ij}, F_{ij} >$ denotes the degree of influence that the factor i has on the factor j.

Step 2: Normalize the neutrosophic aggregated direct-influence matrix, A^G and obtain the matrix B as shown in Eqs. 4 and 5.

$$B = kxA^G \quad (4)$$

$$k = Min\left(\frac{1}{\max\limits_{1\le i<n}\sum_{j=1}^{n} T_{ij}}, \frac{1}{\max\limits_{1\le j<n}\sum_{i=1}^{n} T_{ij}}\right) \quad (5)$$

Step 3: Obtain the total direct-influence matrix, S.

In general, the total direct-influence matrix, S is obtained via the Eq. 6.

Table 4
The properties of the experts.

Expert	Position	Sector	Experience in lean	Importance Value	Importance Weights
E1	Professor Dr.	Education	30+ years	Absolutely important	0.199
E2	Professor Dr.	Education	17 years	Important	0.180
E3	Dr.	Education	10 years	Medium Important	0.121
E4	Engineer	Electric	3 years	Medium Important	0.121
E5	Manager	Hot rolled steel	5 years	Important	0.180
E6	Manager	Marine and energy	8 years	Absolutely important	0.199

$$S = B + B^2 + B^3 + \ldots + B^m = B(I - B)^{-1} \quad (6)$$

Where I represents the identity matrix, $S = \begin{bmatrix} s_{11} & \cdots & s_{1n} \\ \vdots & \ddots & \vdots \\ s_{n1} & \cdots & s_{nn} \end{bmatrix}$ and $s_{ij} = <T_{ij}, I_{ij}, F_{ij}>$

However, similar operations are performed for each element in the neutrosophic set separately. Hence, the required formulations for the truth-membership, indeterminacy-membership, and the falsity-membership functions are provided respectively in Eqs. 7–9.

$$\text{Matrix } [T_{ij}] = B_T(I - B_T)^{-1} \quad (7)$$

$$\text{Matrix } [I_{ij}] = B_I(I - B_I)^{-1} \quad (8)$$

$$\text{Matrix } [F_{ij}] = B_F(I - B_F)^{-1} \quad (9)$$

Step 4: Provide the deneutrosophication of the total direct-influence matrix, S and obtain the deneutrosophicated total direct-influence matrix (S')

Deneutrosophication of the total direct-influence matrix, S, is obtained via Eq. 3. Then, to find the importance value of each factor, a_i and bj values are calculated. The a_i value is the sum of row i as shown in Eq. 10, whereas, the bj value is the sum of column j as shown in Eq. 11.

$$(a_i)_{nx1} = \left[\sum_{j=1}^{n} s'_{ij}\right]_{nx1} \quad (10)$$

$$(b_j)_{1xn} = \left[\sum_{i=1}^{n} s'_{ij}\right]_{1xn} \quad (11)$$

Each factor's importance value depends on the related (a_i+bj, i = j) value. However, the (a_i-bj, i = j) value can be commented in two ways. If it is positive, it is called as "causer" and affects the other factors. Otherwise, it is called as "receiver" and affected by the other factors.

Step 5: Determine the importance values of the factors.

The importance values of the factors are obtained by normalizing the (a_i+bj) values of the factors.

3.2.2. Questionnaire and scoring method

After determining the metrics and sub-metrics, neutrosophic DEMATEL was used to determine the relationships between the metrics and their relative importance weights. For each metric and sub-metric under consideration, literature was reviewed once again to confirm how the metrics were evaluated, i.e. which questions were asked to evaluate or measure the lean indicator and how the answers were analyzed. Different Likert measurement scales were observed, such as 5-point, 7-point, or 10-point. Some used scales in percentages [7], and some used qualitative scales [28], such as from "low" to "high", from "never" to "always, or from "no adoption" to "total adoption". Hence, a questionnaire was prepared for this research, as displayed in Appendix Table B1. A large number of the questions were based on the researches of Karlsson & Åhlström [10], Perez & Sanchez [43], Taj [67], Ihezie & Hargrove [42] and Almomani et al. [7].

Various scale structures were used in the questionnaire. Depending on each question, the appropriate scale was selected. Either a scale of 5, 4, 3, 2, 1 was used, denoting the possible answers from the best to the worst, or a scale of 5,3,1 was selected where it was more appropriate. Moreover, assumptions are determined as follows:

- In case of binary answers, where questions could be only answered in "yes" or "no", the answers were given the scores of 5 and 0, respectively.
- In case of a lean indicator in question is not applied or does not exist at all in the production system under assessment, the score of "0" is given.

Table 5
The neutrosophic aggregated direct-influence matrix (A^G).

	M1	M2	M3	M4	M5
M1	(0.10, 0,80, 0.90)	(0.76, 0.23, 0.23)	(0.69, 0.29, 0.28)	(0.66, 0.31, 0.31)	(0.62, 0.33, 0.34)
M2	(0.86, 0.14, 0.13)	(0.10, 0.80, 0.90)	(0.82, 0.17, 0.18)	(0.67, 0.29, 0.28)	(0.70, 0.29, 0.27)
M3	(0.76, 0.22, 0.23)	(0.80, 0.19, 0.18)	(0.10, 0.80, 0.90)	(0.80, 0.18, 0.19)	(0.35, 0.56, 0.64)
M4	(0.82, 0.17, 0.16)	(0.61, 0.35, 0.35)	(0.79, 0.20, 0.19)	(0.10, 0.80, 0.90)	(0.42, 0.54, 0.57)
M5	(0.81, 0.19, 0.17)	(0.75, 0.24, 0.23)	(0.63, 0.35, 0.36)	(0.51, 0.45, 0.50)	(0.10, 0.80, 0.90)

Note: Performance, Process, Inventory, Supplier, and Human Resources Management correspond to M1, M2, M3, M4, and M5 respectively.

Table 6
Neutrosophic normalized aggregated direct-influence matrix (B).

	M1	M2	M3	M4	M5
M1	(0.03, 0.24, 0.27)	(0.23, 0.07, 0.07)	(0.20, 0.09, 0.08)	(0.20, 0.09, 0.09)	(0.19, 0.10, 0.10)
M2	(0.26, 0.04, 0.04)	(0.03, 0.24, 0.27)	(0.24, 0.05, 0.05)	(0.20, 0.09, 0.08)	(0.21, 0.08, 0.08)
M3	(0.23, 0.06, 0.07)	(0.24, 0.06, 0.05)	(0.03, 0.24, 0.27)	(0.24, 0.05, 0.06)	(0.10, 0.17, 0.19)
M4	(0.25, 0.05, 0.05)	(0.18, 0.10, 0.10)	(0.23, 0.06, 0.06)	(0.03, 0.24, 0.27)	(0.12, 0.16, 0.17)
M5	(0.24, 0.06, 0.05)	(0.22, 0.07, 0.07)	(0.19, 0.10, 0.11)	(0.15, 0.13, 0.15)	(0.03, 0.24, 0.27)

Table 7
The total direct-influence matrix (S).

	M1	M2	M3	M4	M5
M1	(1.18, 0.38, 0.45)	(1.25, 0.21, 0.23)	(1.24, 0.24, 0.26)	(1.16, 0.26, 0.30)	(0.97, 0.31, 0.37)
M2	(1.47, 0.12, 0.13)	(1.18, 0.39, 0.45)	(1.36, 0.16, 0.18)	(1.24, 0.23, 0.25)	(1.05, 0.25, 0.28)
M3	(1.34, 0.17, 0.21)	(1.25, 0.19, 0.21)	(1.08, 0.42, 0.50)	(1.18, 0.21, 0.27)	(0.90, 0.40, 0.50)
M4	(1.32, 0.16, 0.17)	(1.18, 0.26, 0.29)	(1.22, 0.20, 0.23)	(0.98, 0.45, 0.53)	(0.89, 0.40, 0.47)
M5	(1.34, 0.16, 0.18)	(1.24, 0.22, 0.24)	(1.21, 0.26, 0.30)	(1.11, 0.32, 0.39)	(0.82, 0.48, 0.59)

- In case the data cannot be obtained in the production system under assessment, it is assumed that the indicator is not applied or does not exist, hence a score of "0" is given.

In the final phase, all the scorings are normalized and the weighted final leanness score is obtained by incorporating the importance weights of the main metrics. The required operations are illustrated in the application part in detail.

4. An application in the production sector

The proposed methodology is applied across three different companies which are in the sectors of electrical products, hot rolled steel, marine & energy. These firms had experiences in terms of lean techniques implementation for years, and are keen to find out their leanness scores. Data was collected via interviewing participating interviewees and multiple plant visits.

Table 9
Importance weights of the metrics.

Metric	a_i+b_j	Importance Weight (%)
M1	7.272	20.33
M2	7.339	20.52
M3	7.201	20.13
M4	7.129	19.93
M5	6.829	19.09

4.1. Neutrosophic DEMATEL

After determining the main and sub-metrics, neutrosophic DEMATEL technique was utilized to obtain the importance values of the main metrics. The related steps are as follows.

Step 1

As explained before, the first step of neutrosophic DEMATEL is obtaining the neutrosophic aggregated direct relation matrix which includes a pairwise evaluation of the metrics with respect to the influence value regarding the scale indicated in Table 3. The influence degrees have a range from "Very Unimportant" to "Absolutely Important". A group of 6 experts comprises of three lean experts from industry and three academics whose expertises are in lean production were interviewed. Information about the experts (i.e. position, sector, experience), and importance value which is assessed based on their knowledge are provided in Table 4.

Based on their importance values, experts' importance weights are computed via Eq. 1 and represented in Table 4. Afterward, the experts' individual considerations (A^M) which are provided in Appendix Table C1 are aggregated according to Eq. 2 and the neutrosophic aggregated direct-influence matrix (A^G) is obtained as in Table 5.

Step 2

Eq. 4 and Eq. 5 are applied to normalize the neutrosophic aggregated direct-influence matrix and the normalized matrix is obtained as seen in Table 6.

Step 3

After the normalization process, the total direct-influence matrix, S including three elements is obtained via Eqs. 7–9 and indicated in Table 7.

Step 4

The total direct-influence matrix is deneutrosophicated via Eq. 3 and indicated in Table 8.

Table 8
The deneutrosophicated total direct-influence matrix.

	M1	**M2**	**M3**	**M4**	**M5**	a_i	b_j	a_i+b_j	a_i-b_j
M1	0.643	0.769	0.756	0.752	0.723	3.642	3.630	7.272	0.012
M2	0.709	0.639	0.751	0.758	0.778	3.634	3.705	7.339	−0.071
M3	0.749	0.780	0.621	0.777	0.623	3.550	3.651	7.201	−0.102
M4	0.772	0.750	0.783	0.599	0.640	3.543	3.586	7.129	−0.042
M5	0.757	0.768	0.741	0.700	0.550	3.516	3.313	6.829	0.203

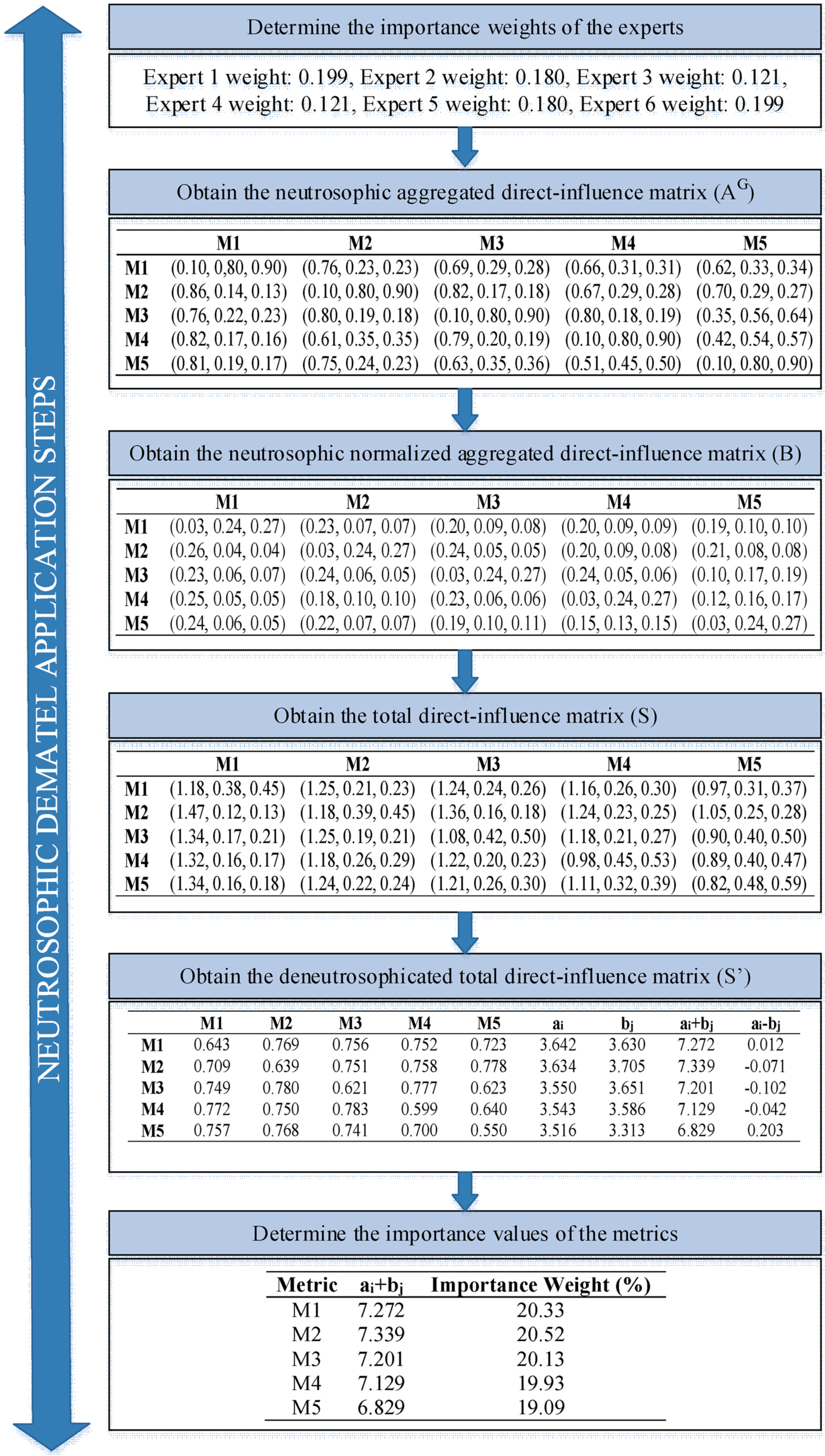


Fig. 2. Flow chart of neutrosophic DEMATEL application steps.

Table 10
Weights and scores of metrics for Company A.

METRIC	NORMALIZED SCORES	METRIC	NORMALIZED SCORES
Performance (Weight: 0.2020)		**PROCESS (Weight: 0.2046)**	
Dock-to-Dock Days	0.40	One Piece Flow	0.47
First Time Through	0.40	Layout/Handling	0.40
On Time Shipment	0.40	Standardization	0.60
Floor Space	0.44	Kaizen	0.48
Sales per Person	0.00	Visual Management	0.30
Average Cost per Unit	0.60		
Average Normalized Score	0.37	**Average Normalized Score**	0.45
INVENTORY (Weight: 0.2008)		**SUPPLIER (Weight: 0.2000)**	
Supermarket	0.00	JIT Delivery	0.53
Lot Size Reduction	0.60	Supplier Involvement	0.47
Pull Control System	0.47	High Quality	0.70
Inventory Turnover	0.40	Kaizen Culture	0.20
Average Normalized Score	0.37	**Average Normalized Score**	0.48
HUMAN RESOURCES MANAGEMENT (Weight: 0.1925)			
Management Commitment	0.35		
Capability Development	0.45		
Multifunctional Teams	0.40		
Team Works	0.40		
Employee Empowerment and Involvement	0.28		
Average Normalized Score	0.38		

Step 5

The importance weights of the main metrics are obtained by normalizing (a_i+bj) values indicated in Table 9. These normalized values will be used as importance weights in the leanness score calculations.

To enhance the visibility and understandability of the N-DEMATEL application, the results of application steps are provided in a consolidated form (see Fig. 2).

4.2. Analysis of the assessment score

Taking into account the assumptions that were explained previously, the score of each sub-metric is calculated by taking the average of all questions' scores under that sub-metric. Each sub-metric is given a score between 0–5, then the obtained scores are normalized via a transformation from 0 to 5 scale to 0–1 scale. Then, the main metric score is obtained by taking the average of all sub-metrics' scores under that main metric.

Finally, the leanness score is obtained by multiplying the score of each main metric by its importance weight and then taking the sum of the main metrics' weighted scores. Hence the weighted sum represents the leanness score.

The weights of metrics and average normalized scores of sub-metrics for the company A are presented in Table 10. The related calculations for the companies B and C are provided in Appendix Tables C2 and C3.

Each main metric's average normalized score is multiplied by the weight of that metric and the sum is calculated. Hence, the obtained score of the companies resulted in 41.02 %, 43.33 %, and 32.82 %, respectively. Moreover, each main metric's score is shown in Fig. 3. Hence, it is also possible to make a detailed analysis by focusing on each main and sub-metric and perform the required actions to improve the system.

Based on the results of the leanness score, companies A and B have the least scores on performance and inventory metrics while the company C has the worst score on the process.

For performance metric, Company A should focus on sales per person sub-metric by constructing a system that measures this sub-metric and set realistic target rates for this and a control mechanism to measure if it is satisfied and Company B should focus on the application of lean accounting techniques and again sales per person index, additionally this company should measure dock-to-dock days precisely.

Company C which has the least lean score should firstly focus on the process related sub-metrics such as application of one-piece flow, layout/handling operations, and standardization, additionally, it should deal with the performance-related sub-metrics such as sales per person and dock-to-dock days.

5. Results and discussion

In this section, sensitivity analysis is performed to elaborate on the results in more detail. Moreover, a comparison is made with classic DEMATEL and finally, representativeness and limitations of the proposed methodology are provided.

5.1. Sensitivity analysis

To further analyze the change in the leanness assessment scores of the companies, a sensitivity analysis concerning metric importance weights is performed. Three scenarios for each metric and fifteen scenarios in total are considered. The analysis with respect to metric 1 (performance) is indicated in Fig. 4 and the others are provided in Appendix Figures D.1–D.4. Considering the sensitivity analysis with respect to performance metric, three importance weights (w1), 0.1,0.3,0.5, are used respectively. As can be inferred from the analysis, company B is affected by the change in the importance weight of metric 1 (Performance) more than the other companies. However, company A is the least affected company among other companies.

Considering the other scenarios, it is concluded that the change in the importance weight of metric 2 (Process) does not have a big effect on the leanness score of the companies A and B but slightly affects company C. Similarly, metric 3 (Inventory) has little effect on company B. Different from metrics 2 (Process) and 3 (Inventory), metric 4 (Supplier) has effects on all the companies. Finally, metric 5 (Human resources management) has little effect on companies B and C.

5.2. Comparison with classic DEMATEL

Different from the conventional optimization problems, there is not the optimum solution in MCDM problems. Instead, the most suitable technique is determined depending on the problem characteristic as in this study. However, the classic DEMATEL which is based on crisp

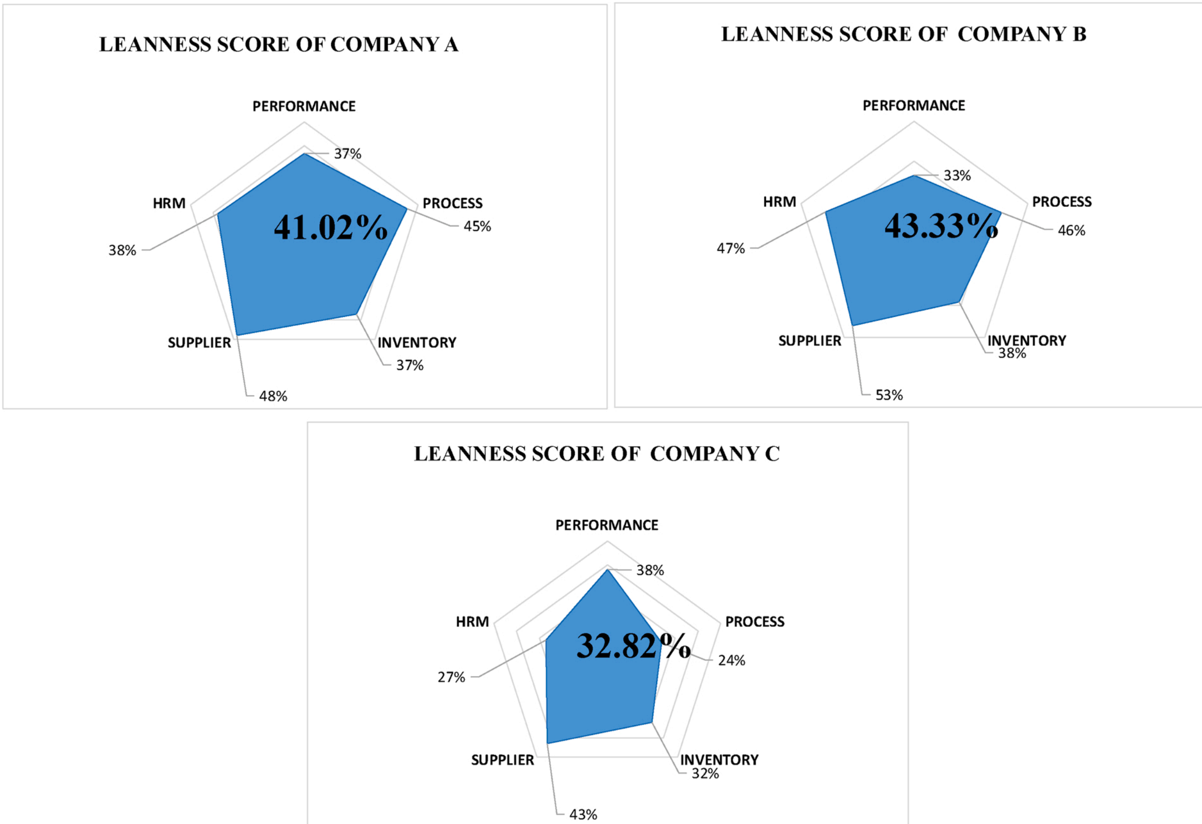


Fig. 3. Leanness scores of the companies and their main-metrics.

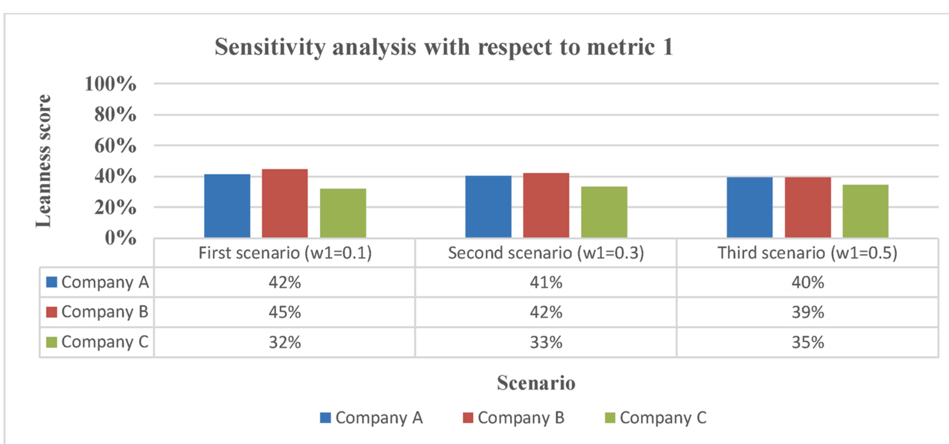
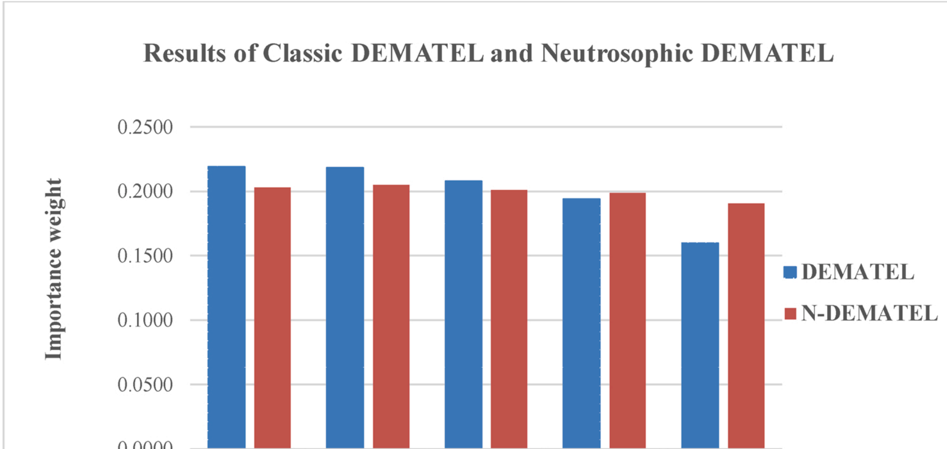


Fig. 4. Sensitivity analysis with respect to performance metric (w1).

evaluations is utilized so as to reveal the differences concerning the obtained importance weights of the metrics. Considering the differences in the application steps of neutrosophic and classic versions of DEMATEL, it is not expected to obtain the same importance weights as indicated in Fig. 5. The biggest difference is seen in the human resources management (fifth) metric. However, there are slight differences in the importance weights of the first four metrics.

5.3. Representativeness and limitations of the proposed methodology

As pointed out by Santos Bento and Tontini [29], to make improvement for any organization, it is required to know the current situation from a multi-dimensional perspective and evaluate it via a thorough assessment system. The proposed methodology not only provides this multi-dimensional perspective but also eliminates bias on human judgment. Suitability and strength of the methodology depend



	M1	M2	M3	M4	M5
DEMATEL	0.2193	0.2184	0.2080	0.1944	0.1599
N-DEMATEL	0.2033	0.2052	0.2013	0.1993	0.1909

Fig. 5. Results of classic DEMATEL and neutrosophic DEMATEL.

on its consideration of the human judgments in terms of truth, indeterminacy, and falsity dimensions. Additionally, the questionnaire provided in the study aids the assessment of the leanness from a multi-dimensional perspective. The multi-dimensional structure together with the properties of neutrosophic DEMATEL indicate that companies can be benefited from applying this methodology to assess their leanness level in a comprehensive way.

The practitioners adopting this methodology should involve a whole range of departments including finance, production, human resources for data collection by completing the questionnaire. Leanness score can then be quickly calculated following the steps outlined in this study.

One of the limitations of the study is that the questionnaire structure is specifically designed for manufacturing industry. However, with small adjustments on the questionnaire,there exists the possibility of its application beyond manufacturing to other sectors, such as service, construction, and others. Another limitation lies in the small number of firms that the proposed methodology has been tested in this study. Despite the fact that the proposed methodology can be easily used in the case companies, the larger number of applications together with more feedback could improve the rigor and robustness of the questionnaire in a more meaningful way.

6. Conclusion

Lean systems have become increasingly important than ever given the global competitive business environment in which companies operate in nearly every sector. Reportedly, the number of lean implementations have increased in recent years, but a leanness assessment is overdue. This study focuses on the leanness assessment which is perceived as the first step of the lean implementation process.

This study begins with identifying the lean metrics and methods that are most frequently used. As a result of the desktop research and interviews with the lean experts, the most frequently used lean metrics are identified and categorized into appropriate groups and sub-groups. A questionnaire is then developed for the purpose of gathering necessary, real-life data of a production system in order to assess the leanness level of a manufacturing company. The results of the questionnaire from three different cases in the manufacturing sector are presented in this study. To clarify the relationship between the main metrics and to determine the importance weights, neutrosophic DEMATEL is applied and leanness scores are obtained. Lastly, to analyze the effect of changes in metric importance weights, sensitivity analysis and comparison of the proposed methodology with classic DEMATEL are performed.

The results of the analysis show that there are no significant differences between metrics in terms of importance weights. However, while the process main metric has the highest importance weight which is not surprising for manufacturing companies, human resources management has the least importance weight. Considering the process metric's high importance weight, it is recommended for manufacturing companies to improve the process related metrics such as standardization, kaizen, and one-piece flow on their lean journey. The scores of the questionnaire also indicate that companies applying lean philosophy are aware of the importance of process and performance metrics. This is evident in the adoption of lean tools, hoping to improve the value of these metrics. Furthermore, the best leanness score for the three cases is from the supplier main metric which shows these three companies' capability to spread the lean philosophy to their supply chain.

Comparing many leanness metrics and effective nature of N-DEMATEL has the potential to make contribution to the knowledge of lean assessment domain. The method can be successfully applied to assess leanness levels of production systems, and it can act as a first step and a guide for companies that aim to make transformation to become a lean enterprise. Future research could include other suitable MCDM methods. An expert system can be developed for monitoring the leanness level and providing suggestions to the managers. Moreover, leanness assessment methods can also be embedded in the enterprise resource planning systems of the companies. Last but not the least, the relationship between the leanness score and other factors such as profitability and economic sustainability can be investigated.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Literature Review Summary Table

Table A1
Literature review summary table.

Authors (Year)	Lean Metrics						Leanness Assessment Methods					
	JIT/ Continuous Flow	Continuous Improvement	Multifunctional Teams	Flexibility	Quality	Other	Simulation	Benchmarking	AHP/ ANP	Fuzzy Logic	Questionnaire Analysis	Other
Abdi [41]		☑	☑	☑	☑	*4,6,7,8,9,24,25,27,30,32,33,				☑		**16,18
Santos Bento & Tontini [29]		☑		☑	☑	*3,5,11,13,1617,25,26,27,28,29,30,31						**8,15
Galankashi et al. [13]		☑		☑	☑	*3,8,11,16		☑			☑	
Jaiswal et al. [30]					☑	*1,11,12,13						**13,14
Narayanamurthy & Gurumurthy [47]	☑	☑	☑		☑	*5,6,7,8,11,16				☑		
Rakhmanhuda & Karningsih [31]					☑	*1,5,7,14,15,16,17				☑		**19
Sangwa & Sangwan [68]					☑	*5,11,15,24,31,				☑		
Thanki & Thakkar [32]						*9,11,16,18,19,20,21,22,23,24				☑		**6
Yadav et al. [39]	☑	☑	☑	☑		*2,4,5,23,32,34,35,36,37			☑		☑	**17
Abreu & Calado [40]		☑			☑	*2,3,5,8,9,23,30,37				☑		
Buonamico et al. [69]	☑	☑	☑		☑	*3,6,9				☑		
Dixena & Kashyap [37]			☑	☑	☑	*1,2,3,4,5,11,16,23,31,39,42						**26
Gonçalves & Salonitis [14]				☑	☑	*1,6,7,37					☑	**21,22,23,24,25
Liu et al. [50]						5,20,38,39,40						**20
Welo & Ringen [33]		☑				4,5,17						**27,28
Al-Ashaab et al. [38]		☑				*24,31,38					☑	
Ali & Deif [70]					☑	*1,2						**1
Elnadi & Shebab [12]	☑	☑		☑	☑	*3,4,5						**2
Maasouman & Demirli [71]	☑		☑		☑	*2,6,7				☑		
Narayanamurthy & Gurumurthy [34]	☑	☑	☑	☑	☑	*1,4,8,9,10						**3
Oleghe & Salonitis [72]					☑	*2,3	☑			☑		
Sharma et al. [73]	☑			☑								**4
Vidyadhar et al. [35]	☑				☑	*3,4,8,10				☑		
Susilawati et al. [28]				☑	☑	*1,9,11				☑	☑	**5
Almomani et al. [7]	☑	☑	☑	☑	☑	*6,8,11			☑		☑	
Pakdil & Leonard [74]	☑	☑	☑		☑	*6,8				☑		
Ram Matawale et al. [45]	☑	☑	☑	☑	☑	*3,6,8				☑		
Wong et al. [27]	☑	☑	☑	☑	☑	*6,10,11			☑		☑	
Amin [49]				☑	☑	*8				☑		
Cil & Turkan [26]	☑		☑	☑	☑	*1,8,11			☑			
				☑	☑	*1,9,11						**2

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Table A1 (*continued*)

Authors (Year)	Lean Metrics						Leanness Assessment Methods					
	JIT/ Continuous Flow	Continuous Improvement	Multifunctional Teams	Flexibility	Quality	Other	Simulation	Benchmarking	AHP/ ANP	Fuzzy Logic	Questionnaire Analysis	Other
Karim & Arif-Uz-Zaman [25]												
Calarge et al. [75]	☑	☑	☑	☑		*8,9					☑	
Ramesh & Kodali [24]					☑	*11			☑			
Sezen et al. [23]					☑	*1,11					☑	
Behrouzi & Wong [22]	☑	☑	☑		☑	*6,11		☑		☑		
Bhasin [21]	☑	☑	☑	☑	☑	*6,8,11					☑	
Saurin et al. [20]	☑		☑		☑	*8,9,11					☑	
Seyedhosseini et al. [19]				☑	☑	*3,11						**6,7
Vinodh & Chintha [76]	☑	☑			☑	*6,8				☑		
Nordin et al. [77]	☑	☑	☑	☑		*3					☑	
Zanjirchi et al. [78]		☑		☑	☑	*10				☑		
DeWayne [16]		☑	☑		☑	*1,11			☑			**10
Fullerton & Wempe [17]				☑	☑	*9,10						**8
Gurumurthy & Kodali [51]	☑			☑	☑	*1		☑				
Ihezie & Hargrove [42]	☑	☑	☑	☑	☑	*3					☑	**5,9
Puvanasvaran et al. [79]			☑	☑	☑	*1					☑	
Bayou & De Korvin [80]	☑	☑	☑	☑	☑	*1		☑		☑		
Degirmenci [81]		☑	☑		☑	*3,9	☑				☑	
Khadem et al. [15]						*1,3	☑					
Taj [67]	☑	☑	☑	☑	☑	*1,6					☑	
Wan & Chen [82]				☑	☑	*11		☑				**2 **10
Ray et al. [83]	☑			☑		*3,8,9						**11
Singh et al. [84]	☑		☑	☑	☑	*1,9				☑		
Srinivasaraghavan & Allada [85]	☑			☑	☑	*8						**12
Doolen & Hacker [86]	☑	☑		☑	☑	*3,6,8,10,11					☑	
Rawabdeh [87]					☑	*1,6					☑	
Taj [44]					☑	*1,11					☑	**9
Kojima & Kaplinsky [88]			☑	☑	☑	*6,9						**10
Soriano-Meier & Forrester [41]			☑	☑	☑	*1					☑	
Detty & Yingling [18]	☑	☑	☑	☑		*3	☑					
Panizzolo [11]						*3,9					☑	
James-Moore & Gibbons [9]	☑	☑	☑	☑	☑	*3,8					☑	
Karlsson & Åhlström [10]	☑	☑	☑			*8,9						**2
TOTAL	30	30	29	36	51		4	5	6	19	22	

*1: Inventory control

**1: DOE and System dynamics

(*continued on next page*)

Table A1 (*continued*)

Authors (Year)	Lean Metrics						Leanness Assessment Methods					
	JIT/ Continuous Flow	Continuous Improvement	Multifunctional Teams	Flexibility	Quality	Other	Simulation	Benchmarking	AHP/ ANP	Fuzzy Logic	Questionnaire Analysis	Other
Other (*/**) Explanations												
						*2: Machine efficiency (TPM)						**2: Performance measurement
	*3: Supplier and customer relationships						**3: Graph Theoretic Approach					
	*4: Management Commitment						**4: Interpretive Structural Modelling (ISM)					
	*5: Process						**5: VSM					
	*6: Elimination of waste						**6: DEMATEL					
	*7: Safety/Ergonomics						**7: Balanced Scorecard					
	*8: Pull instead of push						**8: SEM					
	*9: Employee empowerment						**9: STRATEGOS					
	*10: Cellular manufacturing						**10: Weighing					
	*11: Cost						**11: Factor Analysis					
	*12: Labor productivity improvement						**12: Mahalanobis Taguchi Gram Schmidt System					
	*13: Short lead Time						**13: IF-TOPSIS					
	*14: Time effectiveness						**14: Aggregate Scoring Approach					
	*15: Human Resources						**15: Least Square Path Modelling					
	*16: Delivery						**16: MULTIMOORA					
	*17: Customer						**17: Interactive Structural Modelling					
	*18: Profitability						**18: Delphi Method					
	*19: Market Share						**19: Frequency Analysis					
	*20: Overall Productivity						**20: TOPSIS					
	*21: Hazardous Waste						**21: Rapid Plant Assessment					
	*22: Number of Suppliers						**22: Kobayashi’s 20 Keys					
	*23: Employee Training & Education						**23:Ergonomic Workstation Analysis					
	*24: Information Sharing						**24:Workstation Design Navigator					
	*25: Strategic Planning						**25:Automative Process Diagnostic Standards Tool					
	*26: Problem Solving						**26: 2nd Level Hierarchical lean-Resilient Supply Chain Module					
	*27: Respect for people						**27: Explanatory Lean Product Development Model					
	*28: Overtime						**28: Derivative Assessment Tool					
	*29: Stock Turnover											
	*30: Setup											
	*31: New Product Development											
	*32: Smoothness of Information Flow											
	*33: Culture Improvement											
	*34: Leadership											
	*35: Automation											
	*36: Levelled Production											
	*37: Visual Management											
	*38: Tools & Enablers											
	*39: Planning Ability											
	*40: Resource Allocation											
	*41: Material Logistics											
	*42:Technology											

Appendix B. Questionnaire for Leanness Assessment

Table B1
Questionnaire for leanness assessment.

PERFORMANCE (MAIN METRIC)	
Dock-to-dock days (Sub-metric Under PERFORMANCE)	
1) Dock-to dock days of each shipment is recorded • Yes (5) • Partially recorded (3) • No (0)	2) At what degree do you apply Dock-to-dock day improvement? • Dock-to dock days components are known and there is a standard mechanism to improve it (5) • WIP wait times, Equipment down time, Line stop times, setup times, Overall Equipment Efficiency are measured frequently (3) • Dock to dock day is not known precisely (1) • Dock-to-dock days is not known (0)
First Time Through (Sub-metric Under PERFORMANCE)	
1) What is the percentage of units produced right on the first time? • 95-100 percent (5) • 81-95 percent (4) • 71-80 percent (3) • 51-70 percent (2) • <50 percent (1)	
On-time Shipment (Sub-metric Under PERFORMANCE)	
1) What is the percentage of orders delivered on time that are correct and complete? (On-Time Delivery %) • 95-100 percent (5) • 81-95 percent (4) • 71-80 percent (3) • 51-70 percent (2) • <50 percent (1)	
Floor Space (Sub-metric Under PERFORMANCE)	
1) Do you keep inventory (WIP and/or Finished goods) on the production area? • No (5) • Yes (0) 2) Do you keep tools and equipment which support production on the floor space? • No, all tools and equipment have their assigned area (5) • Some of the tools are kept on the production area (3) • No (0) 3) Are production, walking and vehicle moving areas designated on the floor space? • Yes (5) • No (0)	4) What percentage of personnel are active members of problem-solving teams or quality teams? • 81-100 percent (5) • 51-80 percent (4) • 26-50 percent (3) • 10-25 percent (2) • <10 percent (1) 5) What degree of continuous improvement culture is established in the company? • Problems are solved permanently (5) • Current problems are analyzed and kaizen plans are established (4) • Quantitative goals are established about Kaizen numbers (3) • Kaizen education is established throughout the company (2) • Each team member participates at least one kaizen activity (1)
Sales per person (Sub-metric Under PERFORMANCE)	
1) Do you measure sales per person? (If yes proceed with 2nd question otherwise skip to next sub metric) • Yes (5) • No (0) 2) Are there realistic target values defined and updated for the near future? (If yes proceed with the 3rd question otherwise skip next submetric) • Yes (5) • No (0)	3) What is the percentage of set target values realization rate? • Improvement rate on target values satisfied/oversatisfied. (5) • Sales per person index is improved but undersatisfied (3) • Sales per person index is not improved (1) • Sales per person index is worsened (0)

(continued on next page)

Table B1 (*continued*)

2) What is the number or percentage of tasks in product flow performed by the teams? • High (5) • Moderate (3) • Low (1)	4) How would you rate the interchange-ability of personnel? • Very interchangeable (5) • Moderately interchangeable (3) • Not very interchangeable (1)
•	
Team Works (Sub-metric Under HUMAN RESOURCES MANAGEMENT)	
1) What is the percentage of employees working in teams? • High (5) • Moderate (3) • Low (1) 2) What is the number or percentage of tasks in product flow performed by the teams? • High (5) • Moderate (3) • Low (1)	3) How frequently do employees change tasks within the team? (Every hour, every day, every week?) • More frequently than every week (5) • Every week (3) • Not frequent (1) 4) How would you rate the interchange-ability of personnel? • Very interchangeable (5) • Moderately interchangeable (3) • Not very interchangeable (1)
Employee Empowerment and Involvement (Sub-metric Under HUMAN RESOURCES MANAGEMENT)	
1) How would you rate the involvement of employees, e.g. in Kaizen circles, improvement suggestions, etc.? • All employees are involved (5) • Overall insufficient involvement (3) • Only some of the employees are involved (1) 2) How would you rate the ability of employees to accept responsibility for leadership, planning and quality inspection? • All employees are able to accept responsibility (5) • Some employees are able to accept responsibility (3) • Most employees avoid accepting responsibility and leadership (1) 3) How would you rate the top management's encouragement of employee involvement in the production process? • High (5) • Moderate (3) • Low (1)	4) How would you rate the spirit and cooperation of employees in the company? • High spirit and high cooperation (5) • Moderate (3) • Overall poor spirit and cooperation (1) 5) How would you rate the employees' attitude toward change? • All employees understand the necessity of change and are willing to adapt (5) • Some employees resist change and some have positive attitude (3) • There is resistance of employees toward change (1)
• 51-80 percent (4) • 26-50 percent (3) • 10-25 percent (2) • <10 percent (1)	
Layout/Handling (Sub-metric Under PROCESS)	
1) At what degree cellular layout is applied in the company? • Different product families are manufactured in independent cells (5) • Different product families are manufactured in cells and intercellular movement between cells exists (4) • Group technology is applied for some product families (3) • Group technology concept is not applied in the company (2) • Products are grouped into product families (1) 2) How well could a stranger walking through your plant identify the processes and their sequence? • Processes and their sequences are immediately visible (5) • Most sequences are visible (3) • Not easy (1)	3) What portion of total space is used for storage and material handling? • < 15 percent (5) • 16-30 percent (4) • 30-45 percent (3) • 46-70 percent (2) • 71< percent (1) 4) How would you characterize material movement? • Tote-size or smaller loads, short distances (<25 ft), simple and direct flow pattern (5) • Mostly tote-size loads, bus-route transport, and intermediate distances (3) • Pallet-size (or larger) loads, long distances (>100 ft), complex flow patterns, confusion, and lost material (1)
Standardization (Sub-metric Under PROCESS)	
1) At what degree standard work is applied throughout the company? • Standard operating routines are defined and applied throughout the company (5) • Part production capacity analysis are performed for each product family (4) • Each operation's cycle time is known and maximum number of operations assigned to each worker is calculated (3) • Each product family's process flow is known by the foreman (2) • There is an effort on application of standardization (1)	

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Table B1 (*continued*)

2) What is the number or percentage of tasks in product flow performed by the teams? • High (5) • Moderate (3) • Low (1)	4) How would you rate the interchange-ability of personnel? • Very interchangeable (5) • Moderately interchangeable (3) • Not very interchangeable (1)
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2) How would you rate the ability of employees to accept responsibility for leadership, planning and quality inspection? • All employees are able to accept responsibility (5) • Some employees are able to accept responsibility (3) • Most employees avoid accepting responsibility and leadership (1)	5) How would you rate the employees' attitude toward change? • All employees understand the necessity of change and are willing to adapt (5) • Some employees resist change and some have positive attitude (3) • There is resistance of employees toward change (1)
3) How would you rate the top management's encouragement of employee involvement in the production process? • High (5) • Moderate (3) • Low (1)	

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Table B1 (*continued*)

2) What is the number or percentage of tasks in product flow performed by the teams? • High (5) • Moderate (3) • Low (1)	4) How would you rate the interchange-ability of personnel? • Very interchangeable (5) • Moderately interchangeable (3) • Not very interchangeable (1)
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3) How would you rate the top management's encouragement of employee involvement in the production process? • High (5) • Moderate (3) • Low (1)	

Appendix C. Considerations of experts about lean metric's influence on each other

Table C1
Considerations of experts about lean metric's influence on each other.

Expert 1	**M1**	**M2**	**M3**	**M4**	**M5**
M1	VU	AI	I	I	M
M2	AI	VU	AI	M	AI
M3	AI	AI	VU	AI	M
M4	AI	U	AI	VU	I
M5	AI	AI	AI	AI	VU
Expert 2	**M1**	**M2**	**M3**	**M4**	**M5**
M1	VU	U	U	U	M
M2	AI	VU	AI	M	I
M3	AI	I	VU	M	U
M4	I	M	I	VU	U
M5	I	I	I	U	VU
Expert 3	**M1**	**M2**	**M3**	**M4**	**M5**
M1	VU	I	AI	AI	I
M2	AI	VU	AI	I	M
M3	AI	AI	VU	AI	VU
M4	AI	M	AI	VU	U
M5	I	AI	M	U	VU
Expert 4	**M1**	**M2**	**M3**	**M4**	**M5**
M1	VU	AI	U	I	M
M2	M	VU	AI	I	U
M3	M	AI	VU	I	U
M4	AI	I	M	VU	U
M5	AI	I	U	M	VU
Expert 5	**M1**	**M2**	**M3**	**M4**	**M5**
M1	VU	AI	I	U	AI
M2	AI	VU	M	M	I
M3	M	I	VU	AI	M
M4	I	M	I	VU	VU
M5	AI	M	U	VU	VU
Expert 6	**M1**	**M2**	**M3**	**M4**	**M5**
M1	VU	VU	M	M	VU
M2	I	VU	M	I	VU
M3	U	VU	VU	M	VU
M4	M	I	M	VU	VU
M5	VU	VU	VU	VU	VU

Table C2
Weights and scores of metrics for Company B.

METRIC	NORMALIZED SCORES	METRIC	NORMALIZED SCORES
Performance (Weight: 0.2020)		**PROCESS (Weight: 0.2046)**	
Dock-to-Dock Days	0.10	One Piece Flow	0.47
First Time Through	0.60	Layout/Handling	0.50
On Time Shipment	0.20	Standardization	0.40
Floor Space	0.75	Kaizen	0.64
Sales per Person	0.33	Visual Management	0.30
Average Cost per Unit	0.00		
Average Normalized Score	0.33	**Average Normalized Score**	0.46
INVENTORY (Weight: 0.2008)		**SUPPLIER (Weight: 0.2000)**	
Supermarket	0.60	JIT Delivery	0.40
Lot Size Reduction	0.60	Supplier Involvement	0.20
Pull Control System	0.13	High Quality	0.70
Inventory Turnover	0.20	Kaizen Culture	0.80
Average Normalized Score	0.38	**Average Normalized Score**	0.53
HUMAN RESOURCES MANAGEMENT (Weight: 0.1925)			
Management Commitment	0.72		
Capability Development	0.35		
Multifunctional Teams	0.40		
Team Works	0.20		
Employee Empowerment and Involvement	0.68		
Average Normalized Score	0.47		

Table C3
Weights and scores of metrics for Company C.

METRIC	NORMALIZED SCORES	METRIC	NORMALIZED SCORES
Performance (Weight: 0.2020)		**PROCESS (Weight: 0.2046)**	
Dock-to-Dock Days	0.10	One Piece Flow	0.20
First Time Through	0.60	Layout/Handling	0.20
On Time Shipment	0.60	Standardization	0.20
Floor Space	0.40	Kaizen	0.28
Sales per Person	0.00	Visual Management	0.30
Average Cost per Unit	0.60		
Average Normalized Score	0.38	**Average Normalized Score**	0.24
INVENTORY (Weight: 0.2008)		**SUPPLIER (Weight: 0.2000)**	
Supermarket	0.33	JIT Delivery	0.47
Lot Size Reduction	0.47	Supplier Involvement	0.47
Pull Control System	0.27	High Quality	0.40
Inventory Turnover	0.20	Kaizen Culture	0.40
Average Normalized Score	0.32	**Average Normalized Score**	0.43
HUMAN RESOURCES MANAGEMENT(Weight: 0.1925)			
Management Commitment	0.33		
Capability Development	0.35		
Multifunctional Teams	0.20		
Team Works	0.20		
Employee Empowerment and Involvement	0.28		
Average Normalized Score	0.27		

Appendix D. Sensitivity Figures

Fig. D1, Fig. D2, Fig. D3, Fig. D4

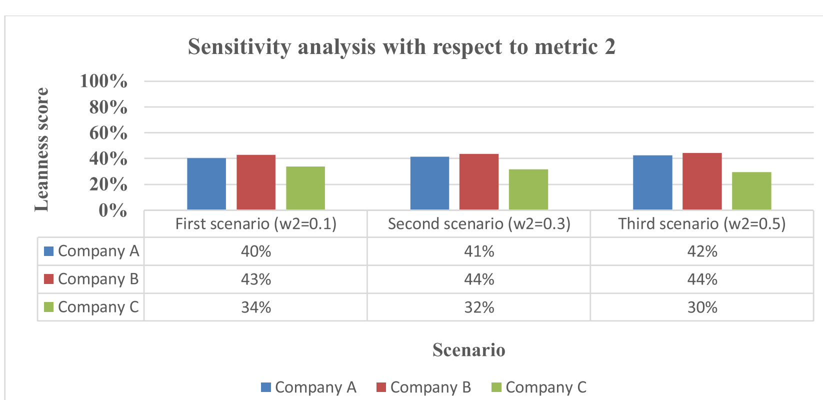

Fig. D1. Sensitivity analysis with respect to process metric (w2).

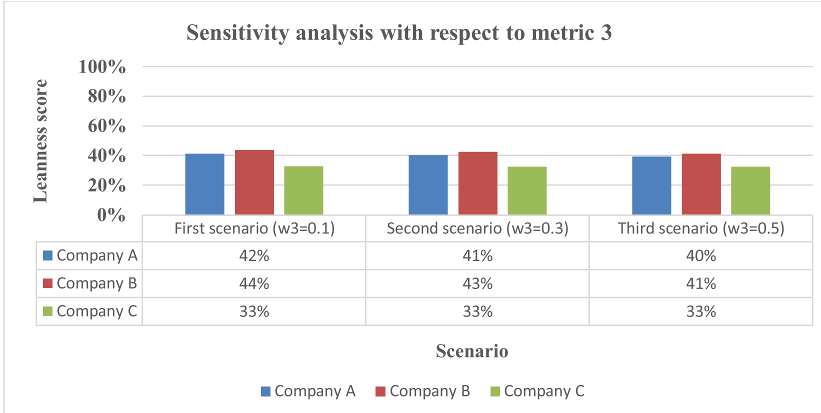

Fig. D2. Sensitivity analysis with respect to inventory metric (w3).

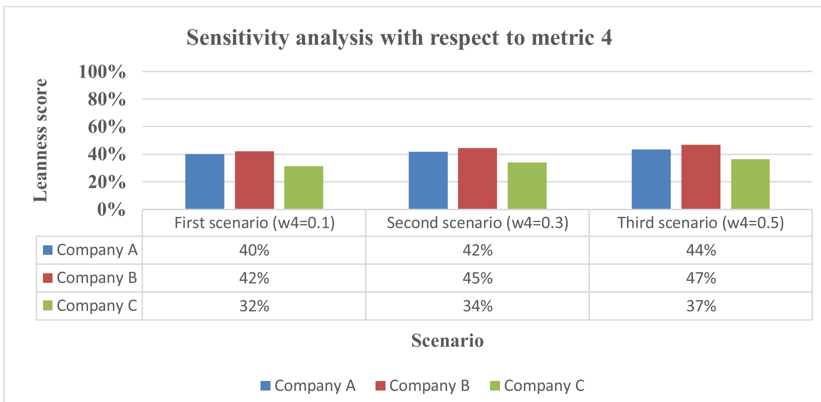

Fig. D3. Sensitivity analysis with respect to supplier metric (w4).

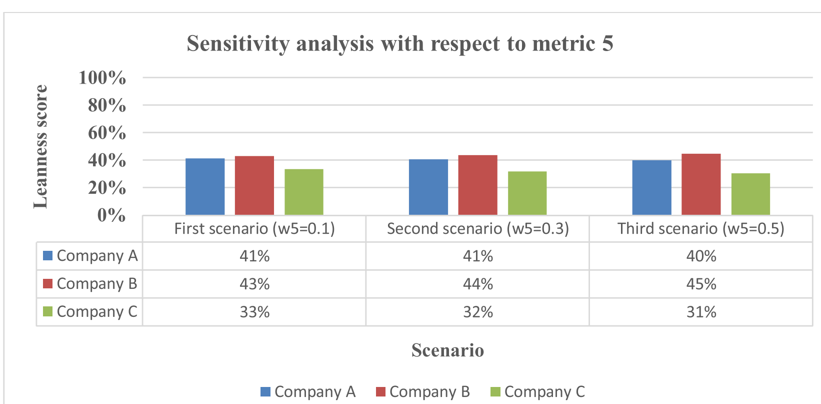

Fig. D4. Sensitivity analysis with respect to human resources management metric (w5).

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