Soft Computing (2021) 25:2253–2265
https://doi.org/10.1007/s00500-020-05294-9

METHODOLOGIES AND APPLICATION

A novel Pythagorean fuzzy AHP and fuzzy TOPSIS methodology for green supplier selection in the Industry 4.0 era

Ahmet Çalık[1]

Abstract

Advances in information and communication technology have created innovator technologies such as cloud computing, Internet of Things, big data analysis and artificial intelligence. These technologies have penetrated production systems and converted them smart. However, this transformation did not only affect production systems, but also differentiated supplier selection processes. In the supplier selection process, the usage of new technologies along with traditional and green criteria extensively has been investigated in recent years. This paper aims to develop a new group decision-making approach based on Industry 4.0 components for selecting the best green supplier by integrating AHP and TOPSIS methods under the Pythagorean fuzzy environment. In the proposed approach, judgments of different experts are expressed by linguistic terms based on Pythagorean fuzzy numbers. The interval-valued Pythagorean Fuzzy AHP method is utilized to determine the criteria weights. The Pythagorean Fuzzy TOPSIS method based on the distances of suppliers is applied to obtain the ranking of the suppliers and determine the most suitable one. Finally, a real case study on an agricultural tools and machinery company is presented to indicate the effectiveness and accuracy of the proposed selection approach.

Keywords Green supplier selection · Industry 4.0 · PFAHP · PFTOPSIS

1 Introduction

The green concept which is one of the important paradigms in supply chain management may be considered as an organizational philosophy. The concept of green supply chain management (GSCM) has attracted more attention due to environmental regulations and consumer pressures on sustainability (Govindan et al. 2015). GSCM is a form of management style that integrates structure of environmental thinking into all supply chain operations such as product design, material selection, purchasing and production process across enables companies to gain more profits and improve their environmental performance by reducing the effects of environmental risks (Mishra et al. 2019).

The GSCM has to start at the beginning of the supply chain, namely procurement of raw materials, and continue at every stage, including recycling or disposal of the product. It is not sufficient to focus on only greenness at the inbound supply chain operations for environmental goals and solutions, and companies should attain the environmental burdens of outbound operations among partners or stakeholders to raise the performance of their suppliers (Banaeian et al. 2018). Therefore, suppliers play a vital role in providing environmental improvements for companies (Mathiyazhagan et al. 2018). Consequently, companies have paid attention to the green supplier selection (GSS) problem while establishing GSCM.

A new and smart (digital) supply chain is created by accessing more information and technology in modern supply chains than ever before. In the current digitalization period, companies are looking for new ways to design supply chain applications and are increasingly dependent on the use of "smart technologies" such as smart supply chain, big data analysis, cloud systems and the Internet of Things (IoT). With the strategic initiative called "Industry 4.0," the introduction of smart technologies into production processes has led companies to seek more innovative

---

Communicated by V. Loia.

✉ Ahmet Çalık
ahmetcalik51@gmail.com

[1] Department of International Trade and Logistics, Faculty of Economics and Administrative Sciences, KTO Karatay University, 42020 Karatay, Konya, Turkey

ways to achieve greater value for themselves and their stakeholders (Wang et al. 2015). Thus, adequate supplier selection and evaluation policies should be reorganized for new business models that come with Industry 4.0 or adapted to new models on existing policies.

Multi-criteria decision-making (MCDM) approaches can be a suitable tool to deal with the GSS problem and compare suppliers. Although there are various studies regarding GSS in the literature under crisp and fuzzy environments, further research is needed with different criteria, expertise and linguistic variables that take into account from the Industry 4.0 window.

The aim of this study is to develop a new hybrid group decision-making approach with the AHP and TOPSIS methods based on Pythagorean fuzzy sets (PFSs) for GSS from the Industry 4.0 window. In order to decide the most suitable supplier, an integrated three-stage MCDM approach is proposed by PFSs. In the first stage, a panel is constituted to gather the opinions of all experts. Then, GSS criteria are narrowed according to the literature survey and experts' opinions from the Industry 4.0 perspective. PFSs are extension of intuitionistic fuzzy sets that gives more freedom to express experts' judgments on the uncertainty and vagueness in decision-making problems. In the second stage, the identified criteria weights are obtained with Pythagorean fuzzy AHP (PFAHP), and in the third stage, potential suppliers are ranked with Pythagorean fuzzy TOPSIS (PFTOPSIS). A case study from the agricultural tools and machinery industry is implemented, and finally a sensitivity analysis is implemented for the validity of the results in terms of the solution of the weights of experts in the TOPSIS method.

2 Literature review

In recent years, many of the studies in the field of GSS have performed with MCDM methods based on standalone and integrated use of fuzzy and conventional sets. In this section, firstly the results of the literature review related to GSS are presented, and then the results of Industry 4.0 components including the green paradigm are provided. Since the 1960s, supplier selection and evaluation have been the focus of many studies not only with traditional criteria but also considering environmental criteria that have revealed GSS. Table 1 provides the details of these studies that are utilized for the solution and evaluation of the GSS problem. Table 2 shows the summary of the studies in which basic components of Industry 4.0 and green paradigm are used together.

As it can be seen from the studies summarized below, the studies that contain the basic components of Industry 4.0 and GSS have been lacking. Moreover, traditional and green criteria are generally taken into consideration in the evaluation of suppliers in GSS. Although supplier selection has investigated with the components of Industry 4.0; almost no attention has been paid to GSS considering the components both PFAHP and PFTOPSIS methods and the components of Industry 4.0 have not been evaluated with environmental concerns. According to Tables 1 and 2, there are few case studies on PFSs; studies generally focus on conventional and type-2 fuzzy sets. Despite GSS has been investigated in the literature in various sectors such as automobile, battery and textile—to the best knowledge of the authors—a new GSS approach for the agricultural tools and machinery industry needs extra research.

3 Proposed green supplier selection approach under Pythagorean fuzzy environment

In this study, a group decision-making approach is proposed for GSS approach by using hybrid AHP with TOPSIS methods under PFSs. In the first stage, GSS criteria and basic components of Industry 4.0 with green paradigm are identified from the literature review. In the second stage, using the opinion of decision-makers, the PFAHP method is applied to specify the weight of all criteria. At the last stage, the PFTOPSIS method is utilized to rank each alternative. Figure 1 shows the flow chart of the proposed GSS approach.

3.1 Preliminaries

In this section, basic concepts and definitions of PFSs are presented. PFSs are firstly proposed by Yager (2014) as the generalization to the intuitionistic fuzzy sets. Therefore, PFSs are more powerful and flexible for solving problems involving uncertainty (Ilbahar et al. 2018; Gul 2018; Gul and Ak 2018; Karasan et al. 2018).

Fuzzy set theory has been applied in a wide range of areas by different research works. Additionally, fuzzy set theory has been utilized in different parts of mathematics such as convergence of series for fuzzy real numbers (Tripathy and Das 2012), paranormed sequence spaces of fuzzy numbers (Tripathy and Debnath 2013), p-absolutely summable sequence of interval numbers (Dutta and Tripathy 2016), p-bounded variation of fuzzy real number sequences (Tripathy and Das 2019) and neutrosophic indeterminacy function (Das et al. 2020).

In PFSs, unlike the intuitionistic fuzzy sets, the sum of membership and non-membership degrees may exceed 1, but the sum of squares may not (Zhang and Xu 2014; Zeng et al. 2016; Karasan et al. 2018). This situation is given below in Definition 1.

Table 1 A brief summary about GSS studies

	Method	Criteria	Illustrative example
Lee et al. (2009)	Fuzzy AHP	Quality, technology capability, total product life cycle cost, green image, pollution control, environment management, green product, green competencies	TFT–LCD manufacturer
Jiun-Shen et al. (2012)	Fuzzy AHP	Supplier criteria, product performance criteria, service performance criteria, cost criteria, environmental management criteria and related sub-criteria	A hand tool industry
Yu and Hou (2016)	Multiplicative AHP	Product performance, supplier criteria, cooperation and development potential, green performance and related sub-criteria	An automobile manufacturing company
Liao et al. (2016)	Fuzzy AHP, fuzzy ARAS and MSGP	Purchase cost, quality service, technology capability, environment skill, delivery performance	A watch firm
Govindan et al. (2017)	Revised Simos procedure and PROMETHEE	Cost, quality, delivery, environmental impacts, technology capability and related sub-criteria	A food processing industry
Qin et al. (2017)	TODIM with interval type-2 fuzzy sets	Green product innovation, green image, use of environmentally friendly technology, resource consumption, green competencies, environment management, quality management, total product life cycle cost, pollution production, staff environmental training	An automobile manufacturing enterprise
Mousakhani et al. (2017)	Interval type-2 fuzzy TOPSIS	Cost, quality, delivery, technology, environmental competency, organization, green image	A battery company
Yazdani et al. (2017)	DEMATEL, QFD, COPRAS and MOORA	Financial stability, environmental management systems, waste disposal program, management commitment, quality control systems, manufacturing, facility, reverse logistics	A dairy company
Banaeian et al. (2018)	Fuzzy TOPSIS, VIKOR and GRA	Service level, quality, price, environmental management systems	An edible vegetable oils manufacturer
Wu et al. (2019)	Interval type-2 fuzzy BWM and VIKOR method	Green product innovation, environmental regime, use of green technology, product quality management, total green product cost, resource consumption, environmental pollution of production,	An electronic enterprise
Gupta et al. (2019)	Fuzzy AHP, MABAC, WASPAS, TOPSIS	Resource consumption, staff environment training, service level, eco-design, green image, environmental management system, price/cost, pollution control, quality	An automotive industry
Liang and Chong (2019)	Hesitant fuzzy QUALIFLEX approach	Pollution control, green competencies, eco-design, green image, environmental management system, commitment of GSCM from managers, use of environmentally friendly technology, use of environmentally friendly materials, staff training,	HZMB megaproject
Mishra et al. (2019)	Hesitant fuzzy WASPAS	Quality, technological, flexibility, financial capability, culture innovativeness, eco-design, environmental management system, green product, management commitment, green technology	Illustrative example
Ulutaş et al. (2019)	Fuzzy extension of range of value and a new MADM model	Cost, defective rate, late delivery rate, technological capability, technical assistance, pollution control, environmental management, green transportation, green warehousing	A textile company
Yucesan et al. (2019)	BWM and interval type-2 fuzzy TOPSIS	Environmental, social, quality, service, risk, cost/price, capability, business structure	A plastic injection molding facility
Liou et al. (2019)	DEMATEL, DANP and MOORA-AS	Green production, green design, collaboration with suppliers, control of nonconforming environmental production, green purchasing, control of in-process environmental substances, control of outgoing environmental substances, warehousing management	An electronics company
Rouyendegh et al. (2020)	Intuitionistic Fuzzy TOPSIS	Quality, cost, service and delivery, sustainability, technology, green manufacturing system, green supplier image, cooperation, green application, environmental management and control	A company

Table 2 Summary of basic components of Industry 4.0 with green paradigm

	Method	Features of Industry 4.0 and green components	Illustrative example
Erdogan et al. (2018)	Fuzzy AHP and VIKOR	Leadership, Customer, product, operation, culture, people, governance, technology, quality, organization	–
Demircan Keskin et al. (2019)	AHP and TOPSIS	Use of intelligent inventory control, degree of supply chain integration and communication, visibility through channels, supply chain flexibility, customer focus level, lead time improvement, supply chain security	A company in the apparel industry
Nascimento et al. (2019)	A qualitative research	Product life cycle, selective waste collection, waste sorting, waste treatment, product printing, product assembly, product selling	–
Sachdeva et al. (2019)	Shannon's entropy and intuitionistic fuzzy TOPSIS	Cost/price, rejection rate, delivery delay, Industry 4.0 technologically enabled, relationship	An automobile manufacturer
Liu and De Giovanni (2019)	Supply chain model	Robotics, automated guided vehicles, 3D printing	Automotive sector
Jena et al. (2020)	The data collection	Cyber-Physical Systems (CPS), IoT, cloud computing, cognitive computing	A cement factory
Hasan et al. (2020)	Decision Support System, TOPSIS and Multi-Choice Goal Programming	Digitalization, traceability, supplier's resource flexibility, cybersecurity risk management, agility, supply chain density, supply chain complexity, re-engineering, automation disruption, information management, supplier reliability, supply chain visibility and so on.	Hypothetical case study
Ramirez-Peña et al. (2020)	Conceptual model	Additive manufacturing, big data, cloud computing, augmented reality, autonomous robots, automatic vehicles, blockchain, cybersecurity, horiz. & vert. integ. system, artificial intelligence, IoT, simulation	–
Chen et al. (2020)	Rough-fuzzy DEMATEL-TOPSIS	Green design in a digital way, green purchasing based on a digital platform, green and smart manufacturing, internal management awareness of using smart technologies for enhancing green development, green and smart logistics	Case study in new energy vehicle transmission
Dev et al. (2019)	Bass diffusion model and Taguchi experimental design	Interoperability/interconnections and real-time capabilities, service orientation, virtualization and decentralization, procurement cost of manufacturer with recycled-material supplier, procurement cost of recycled-material supplier	Simulation

Definition 1 Let a set X be a universe of discourse. A PFS P is an object having the form (Zhang and Xu 2014):

$$P = \{\langle x, P(\mu_P(x), v(x))\rangle | x \in X\} \quad (1)$$

where $\mu_P(x) : X \mapsto [0, 1]$ defines the degree of membership and $v_P(x) : X \mapsto [0, 1]$ defines the degree of non-membership of the element $x \in X$ to P, respectively, and, for every $x \in X$, it holds:

$$0 \le \mu_P(x)^2 + v_P(x)^2 \le 1 \quad (2)$$

For any PFS P and $x \in X$, $\pi_P(x) = \sqrt{1 - \mu_P^2(x) - v_P^2(x)}$ is called the degree of indeterminacy of x to P.

Definition 2 Let $\beta_1 = P\left(\mu_{\beta_1}, v_{\beta_1}\right)$ and $\beta_2 = P\left(\mu_{\beta_2}, v_{\beta_2}\right)$ be two Pythagorean fuzzy numbers, and $\lambda > 0$, then the operations on these two Pythagorean fuzzy numbers are defined as follows (Zhang and Xu 2014; Zeng et al. 2016):

$$\beta_1 \oplus \beta_2 = P\left(\sqrt{\mu_{\beta_1}^2 + \mu_{\beta_2}^2 - \mu_{\beta_1}^2 \mu_{\beta_2}^2}, v_{\beta_1} v_{\beta_2}\right) \quad (3)$$

$$\beta_1 \otimes \beta_2 = P\left(\mu_{\beta_1} \mu_{\beta_2}, \sqrt{v_{\beta_1}^2 + v_{\beta_2}^2 - v_{\beta_1}^2 v_{\beta_2}^2}\right) \quad (4)$$

$$\lambda \beta_1 = P\left(\sqrt{1 - \left(1 - \mu_{\beta_1}^2\right)^{\lambda}}, \left(v_{\beta_1}\right)^{\lambda}\right), \quad \lambda > 0 \quad (5)$$

$$\beta_1^{\lambda} = P\left(\left(\mu_{\beta_1}\right)^{\lambda}, \sqrt{1 - \left(1 - v_{\beta_1}^2\right)^{\lambda}}\right), \quad \lambda > 0 \quad (6)$$

Definition 3 Let $\beta_1 = P\left(\mu_{\beta_1}, v_{\beta_1}\right)$ and $\beta_2 = P\left(\mu_{\beta_2}, v_{\beta_2}\right)$ be two Pythagorean fuzzy numbers, a nature quasi-ordering on the Pythagorean fuzzy numbers is defined as follows (Zhang and Xu 2014):

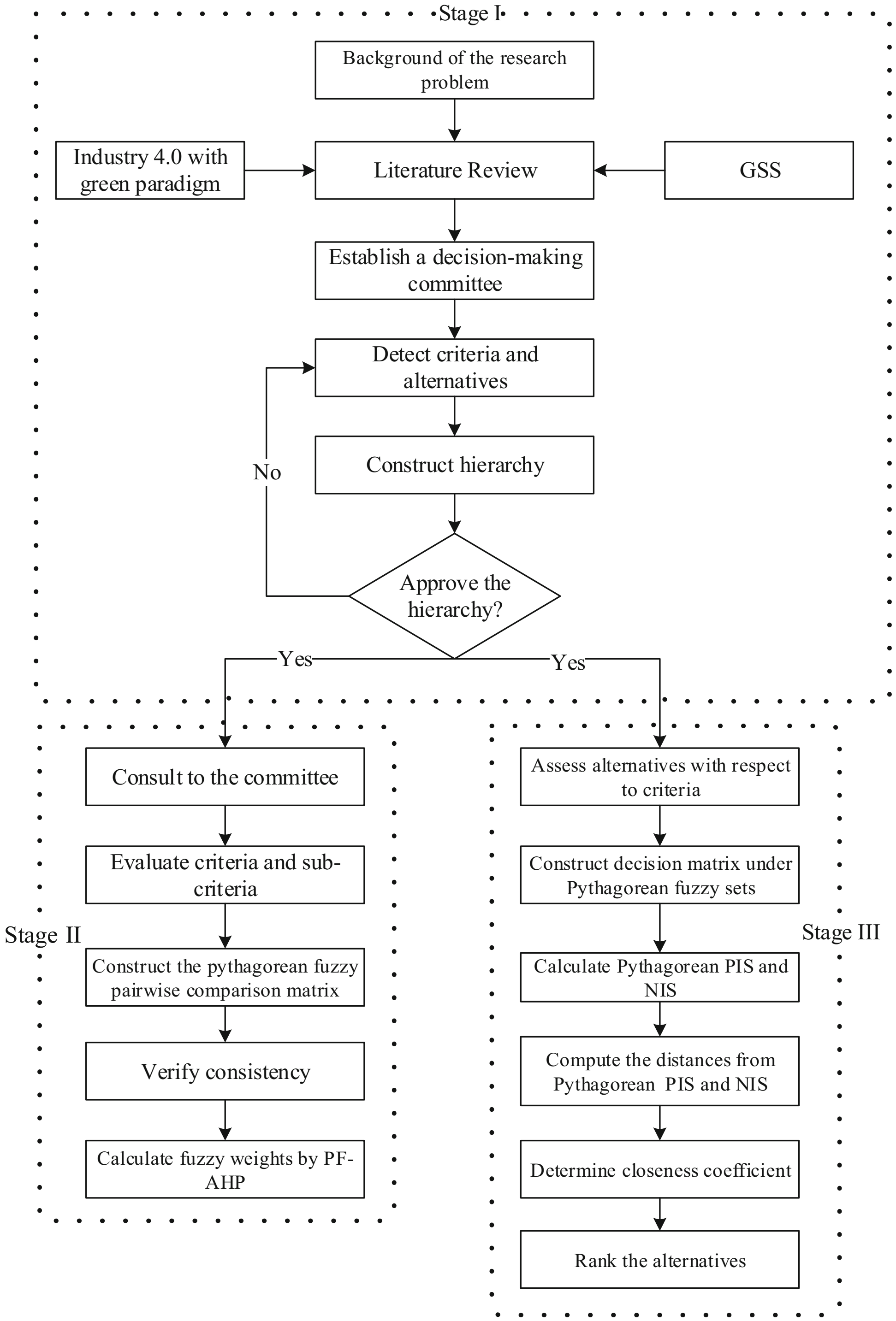

Fig. 1 Flow chart of the proposed GSS approach

$\beta_1 \geq \beta_2$ if and only if $\mu_{\beta_1} \geq \mu_{\beta_2}$ and $v_{\beta_1} \leq v_{\beta_2}$

To compare the magnitude of two Pythagorean fuzzy numbers, a score function is developed by (Zhang and Xu 2014) as follows:

$$s(\beta_1) = \left(\mu_{\beta_1}\right)^2 - \left(v_{\beta_1}\right)^2. \tag{7}$$

Definition 4 Based on the score functions proposed above, the following laws are defined to compare two Pythagorean fuzzy numbers (Zhang and Xu 2014):

(i) If $s(\beta_1) < s(\beta_2)$, then $\beta_1 < \beta_2$,

(ii) If $s(\beta_1) > s(\beta_2)$, then $\beta_1 > \beta_2$,
(iii) If $s(\beta_1) = s(\beta_2)$, then $\beta_1 \sim \beta_2$.

Definition 5 After the judgments of the decision-makers are converted into the interval-valued Pythagorean fuzzy numbers (IVPFNs), these IVPFNs are aggregated using the interval-valued Pythagorean fuzzy weighted geometric (IVPFWG) operator presented in Eq. (8): IVPFWG: $\tilde{P}^n \to \tilde{P}$, where

$$\mathrm{IVPFWG}(\tilde{p}_1, \tilde{p}_2, \ldots, \tilde{p}_n) = \left(\left[\prod_{j=1}^{n} \left(\mu_{\alpha_j}^{L}\right)^{w_j}, \prod_{j=1}^{n} \left(\mu_{\alpha_j}^{U}\right)^{w_j} \right], \left[\prod_{j=1}^{n} \left(\nu_{\alpha_j}^{L}\right)^{w_j}, \prod_{j=1}^{n} \left(\nu_{\alpha_j}^{U}\right)^{w_j} \right] \right) \tag{8}$$

where n is the number of decision-makers, and $w_j = (w_1, w_2, \ldots, w_n)^{\mathrm{T}}$ be the weight vector of $\tilde{p}_j$ with $\sum_{j=1}^{n} w_j = 1$ (Peng and Yang 2016).

Definition 6 The individual assessments of decision-makers are combined using the Pythagorean fuzzy weighted averaging (PFWA) operator as follows:

$$\tilde{r}_{ij} = \mathrm{PFWA}\left(\tilde{r}_{ij}^{1}, \tilde{r}_{ij}^{2}, \ldots, \tilde{r}_{ij}^{k}\right) = = \left(\sqrt{1 - \prod_{k=1}^{l} \left(1 - \left(u_{ij}^{k}\right)^{2}\right)^{w_k}}, \prod_{k=1}^{l} \left[\nu_{ij}^{k}\right]^{w_k} \right), \tag{9}$$

where $\tilde{r}_{ij}^{k} = \left(u_{ij}^{k}, \nu_{ij}^{k}\right)$ is the Pythagorean fuzzy value provided by decision-maker k, on the assessment of A_i in relation to C_j $(i = 1, 2, \ldots, m, = 1, 2, \ldots, n)$.

3.2 PFAHP

The steps of PFAHP are presented as follows.

Step 1: The pairwise comparison matrix $A = (a_{ik})_{m \times m}$ is constructed based on the linguistic evaluation of experts. The linguistic terms that are given (Ilbahar et al. 2018) are presented in Table 3.

Step 2: The difference matrices $D = (d_{ik})_{m \times m}$ between the lower and upper values of the membership and non-membership functions are calculated using Eqs. (10) and (11):

$$d_{ik_L} = \mu_{ik_L}^{2} - \nu_{ik_U}^{2}, \tag{10}$$

$$d_{ik_U} = \mu_{ik_U}^{2} - \nu_{ik_L}^{2}. \tag{11}$$

Step 3: Interval multiplicative matrix $S = (s_{ik})_{m \times m}$ is computed using Eqs. (12) and (13):

$$s_{ik_L} = \sqrt{1000^{d_{ik_L}}}, \tag{12}$$

$$s_{ik_U} = \sqrt{1000^{d_{ik_U}}}. \tag{13}$$

Step 4: The determinacy value $\tau = (\tau_{ik})_{m \times m}$ is calculated using Eq. (14):

$$\tau_{ik} = 1 - \left(\mu_{ik_U}^{2} - \mu_{ik_L}^{2}\right) - \left(\nu_{ik_U}^{2} - \nu_{ik_L}^{2}\right). \tag{14}$$

Step 5: The determinacy degrees are multiplied with $S = (s_{ik})_{m \times m}$ matrix for obtaining the matrix of weights, $T = (t_{ik})_{m \times m}$ before normalization using Eq. (15).

$$t_{ik} = \left(\frac{s_{ik_L} + s_{ik_U}}{2}\right)\tau_{ik}. \tag{15}$$

Step 6: The priority weights w_i of criteria are normalized by using Eq. (16):

Table 3 Linguistic terms for importance weights of criteria

Linguistic variables	Pythagorean fuzzy numbers			
	μ_L	μ_U	ν_L	ν_U
Certainly Low Importance—CLI	0.00	0.00	0.90	1.00
Very Low Importance—VLI	0.10	0.20	0.80	0.90
Low Importance—LI	0.20	0.35	0.65	0.80
Below Average Importance—BAI	0.35	0.45	0.55	0.65
Average Importance—AI	0.45	0.55	0.45	0.55
Above Average Importance—AAI	0.55	0.65	0.35	0.45
High Importance—HI	0.65	0.80	0.20	0.35
Very High Importance—VHI	0.80	0.90	0.10	0.20
Certainly High Importance—CHI	0.90	1.00	0.00	0.00
Exactly Equal—EE	0.1965	0.1965	0.1965	0.1965

$$w_i = \frac{\sum_{k=1}^{m} t_{ik}}{\sum_{i=1}^{m} \sum_{k=1}^{m} t_{ik}}. \tag{16}$$

3.3 PFTOPSIS

The five steps of the procedure of PFTOPSIS approach under PFSs environment are presented as follows:

Step 1: Pythagorean fuzzy number-based decision matrix $R = \left(C_j(x_i)\right)_{m \times n}$ is constructed. Here, $C_j (j = 1, 2, \ldots, n)$ and $x_i (i = 1, 2, \ldots, m)$ refer to the values of criteria and alternatives. The matrix form is as follows:

$$R = \left(C_j(x_i)\right)_{m \times n} = \begin{pmatrix} P(u_{11}, v_{11}) & P(u_{12}, v_{12}) & \ldots & P(u_{1n}, v_{1n}) \\ P(u_{21}, v_{21}) & P(u_{22}, v_{22}) & \ldots & P(u_{2n}, v_{2n}) \\ \vdots & \vdots & \vdots & \vdots \\ P(u_{m1}, v_{m1}) & P(u_{m2}, v_{m2}) & \ldots & P(u_{mn}, v_{mn}) \end{pmatrix}.$$

Step 2: Pythagorean fuzzy positive ideal solution (PIS) and negative ideal solutions (NIS) are determined using Eqs. (17, 18) as follows:

$$x^+ = \left\{ C_j, \max_i s\left(C_j(x_i)\right) | j = 1, 2, \ldots, n \right\}$$

$$= \left\{ \langle C_1, P\left(u_1^+, v_1^+\right) \rangle, \langle C_2, P\left(u_2^+, v_2^+\right) \rangle, \ldots, \langle C_n, P\left(u_n^+, v_n^+\right) \rangle \right\}, \tag{17}$$

$$x^- = \left\{ C_j, \min_i s\left(C_j(x_i)\right) | j = 1, 2, \ldots, n \right\}$$

$$= \left\{ \langle C_1, P\left(u_1^-, v_1^-\right) \rangle, \langle C_2, P\left(u_2^-, v_2^-\right) \rangle, \ldots, \langle C_n, P\left(u_n^-, v_n^-\right) \rangle \right\}. \tag{18}$$

Step 3: In the third step, distances from Pythagorean fuzzy PIS and NIS are determined using Eqs. (19, 20) as follows:

$$\begin{aligned} D(x_i, x^+) &= \sum_{j=1}^{n} w_j d\left(C_j(x_i), C_j(x^+)\right) \\ &= \frac{1}{2} \sum_{j=1}^{n} w_j \left(\left| (\mu_{ij})^2 - \left(\mu_j^+\right)^2 \right| \right. \\ &\quad \left. + \left| (v_{ij})^2 - \left(v_j^+\right)^2 \right| + \left| (\pi_{ij})^2 - \left(\pi_j^+\right)^2 \right| \right), \end{aligned} \tag{19}$$

$$\begin{aligned} D(x_i, x^-) &= \sum_{j=1}^{n} w_j d\left(C_j(x_i), C_j(x^-)\right) \\ &= \frac{1}{2} \sum_{j=1}^{n} w_j \left(\left| (\mu_{ij})^2 - \left(\mu_j^-\right)^2 \right| + \left| (v_{ij})^2 - \left(v_j^-\right)^2 \right| \right. \\ &\quad \left. + \left| (\pi_{ij})^2 - \left(\pi_j^-\right)^2 \right| \right). \end{aligned} \tag{20}$$

for Eqs. (17, 18) $i = 1, 2, \ldots, n$. In general, the smaller $D(x_i, x^+)$ the better the alternative x_i and the bigger $D(x_i, x^-)$ the better the alternative x_i and let $D_{\min}(x_i, x^+) = \min_{1 \le i \le m} D(x_i, x^+)$ and $D_{\max}(x_i, x^-) = \max_{1 \le i \le m} D(x_i, x^+)$.

Step 4: Fourthly, the revised closeness $\xi(x_i)$ of the alternative x_i is computed using Eq. (21) as follows:

$$\xi(x_i) = \frac{D(x_i, x^-)}{D_{\max}(x_i, x^-)} - \frac{D(x_i, x^+)}{D_{\min}(x_i, x^+)}. \tag{21}$$

Step 5: Finally, the best-ranking order of the alternatives is determined. The alternative with the highest revised coefficient value is the best alternative.

4 An empirical case study

Production systems have been passed to new levels in parallel with the advancement in information technologies. In response to global competition, it has caused organizations to change their core competencies, improve the current environment, and develop new business models for themselves and their stakeholders. In this section, the application of the proposed GSS approach is carried out by the managers of an agricultural tool manufacturer (expressed as XYZ) located in Turkey. The purpose of the managers is to determine the performance of the suppliers by exploring the ranking of importance of the GSS criteria from the Industry 4.0 window. The company that generally produces lawnmowers continues development in the sector by increasing its product range without compromising the understanding of quality and continuous development, and desires to apply its environmental policy in the entire supply chain, including cooperation actions with all suppliers considering Industry 4.0 practices. In view of this situation, GSS has been identified as a necessary decision-making activity for the XYZ company.

4.1 Problem description

XYZ company wants to choose the best green supplier considering the Industry 4.0 components. A panel consisting of four decision-makers was designed to evaluate suppliers. The data collection process was carried out by face to face interview. Four decision-makers denoted by {DM1, DM2, DM3, DM4} from different departments of the company have been invited to provide feedback on the proposed approach. It has been decided that five suppliers specified by $\{S1, S2, S3, S4, S5\}$ can procure the required part. In order to select green suppliers and create a decision-making tool in the evaluation, at first the relevant criteria must be determined correctly. In Sect. 2, the ten most common environmental criteria are identified. The selection of criteria and sub-criteria in the evaluation process was limited based on the opinions of the decision-makers and the literature review and given in Table 4.

4.2 Application of PFAHP to determine of criteria weights

The PFAHP method is used to obtain the weights of the criteria. All calculations are carried out by considering all criteria are benefit ones. The decision-makers expressed their views about the criteria by using linguistic terms that

Table 4 Evaluation criteria and their descriptions for assessment of suppliers

Criteria	Sub-criteria	Definition	Related source
Delivery ($C1$)	Robotics, Automated Guided Vehicles ($C11$)	Robotics is an important innovation technology that enables companies to overcome complex tasks and improve productivity by reducing errors (Liu and De Giovanni 2019)	Liu and De Giovanni (2019), Ramirez-Peña et al. (2020)
	Service level ($C12$)	Service level is the ability of companies to meet customer requests and needs timely delivery, service and supply capacity	Banaeian et al. (2018)
Pollution control ($C2$)	Process safety and environmental control ($C21$)	Pollution control includes the reduction of air emissions, waste water and solid waste etc.	Hashemi et al. (2015), Gupta et al. (2019)
	Lean automation ($C22$)	Lean Automation is an extension of lean manufacturing principles, so that repeated and value-adding tasks are automated in order to meet market demands with higher interchangeability and shorter information flows	Satoglu et al. (2018)
Production ($C3$)	IoT and CPS ($C31$)	The IoT is the transmission of data received from one device to another device, that is, the communication of the devices with each other. CPS (Cyber-Physical Systems) are software-based production systems that can communicate with each other and other materials via the internet	Hermann et al. (2016), Uslu et al. (2019)
	Cloud Computing ($C32$)	Cloud computing is the general name for internet-based computing services that can be used at any time and shared among users for computers and other devices	Xing et al. (2016)
	Big data analytics ($C33$)	From a general perspective, the continuous production of information in cyber-physical systems will require the analysis and measurement of informations after a certain period of time (Niesen et al. 2016). BDA allows processing data to analyze large amounts of unprocessed data produced by smart devices and smart machines and to avoid quality problems	Turanoglu Bekar et al. (2019), Ramirez-Peña et al. (2020)
Quality ($C4$)	3D printing and augmented reality ($C41$)	3D Printing, also called additive manufacturing, is the conversion of three-dimensional objects in the computer environment to physical objects	Santos et al. (2017), Chen and Lin (2017)
	Quality 4.0 ($C42$)	Quality 4.0 is the production state of digitally developed factory structures and processes that increase productivity and flexibility in factories and supply chain by using real-time data from Industry 4.0 technologies	Angel (2019), Küpper et al. (2019)
($C5$) Environmental representation	Green image ($C51$)	Green image represents ratio of green customers to total customers	Jiun-Shen et al. (2012), Mousakhani et al. (2017), Gupta et al. (2019)
	Green design ($C52$)	It includes information such as the use of digital technology to improve environmental design, energy consumption, emission, pollution and sharing of maintenance-related information	Chen et al. (2020)

Table 5 Pairwise comparison of main with respect to experts' judgments

	*C*1	*C*2	*C*3	*C*4	*C*5
*C*1	EE, EE, EE, EE	AAI, HI, AAI, VHI	AAI, AAI, CLI, BAI	AAI, BAI, LI, BAI	CHI, CHI, HI, HI
*C*2	BAI, LI, BAI, VLI	EE, EE, EE, EE	AAI, LI, CLI, CLI	AAI, VLI, VLI, VLI	CHI, AI, AI, AAI
*C*3	BAI, BAI, CHI, AAI	BAI, HI, CHI, CHI	EE, EE, EE, EE	AAI, BAI, AAI, AI	HI, VHI, VHI, VHI
*C*4	BAI, AAI, HI, AAI	BAI, VHI, VHI, VHI	BAI, AAI, BAI, AI	EE, EE, EE, EE	AAI, HI, CHI, VHI
*C*5	CLI, CLI, LI, LI	CLI, AI, AI, BAI	LI, VLI, VLI, VLI	BAI, LI, CLI, VLI	EE, EE, EE, EE

Table 6 Aggregated pairwise comparison matrix of main criteria

	*C*1	*C*2	*C*3	*C*4	*C*5
*C*1	([0.197, 0.197], [0.197, 0.197])	([0.630, 0.743], [0.222, 0.345])	([0.000, 0.000], [0.496, 0.602])	([0.341, 0.463], [0.512, 0.624])	([0.765, 0.894], [0.000, 0.187])
*C*2	([0.222, 0.345], [0.630, 0.743])	([0.197, 0.197], [0.197, 0.197])	([0.000, 0.000], [0.655, 0.775])	([0.153, 0.269], [0.651, 0.757])	([0.563, 0.666], [0.000, 0.342])
*C*3	([0.496, 0.602], [0.000, 0.371])	([0.655, 0.775], [0.000, 0.218])	([0.197, 0.197], [0.197, 0.197])	([0.467, 0.569], [0.417, 0.519])	([0.760, 0.874], [0.119, 0.230])
*C*4	([0.512, 0.624], [0.341, 0.463])	([0.651, 0.757], [0.153, 0.269])	([0.417, 0.519], [0.467, 0.569])	([0.197, 0.197], [0.197, 0.197])	([0.712, 0.827], [0.000, 0.237])
*C*5	([0.000, 0.000], [0.765, 0.894])	([0.000, 0.000], [0.563, 0.666])	([0.119, 0.230], [0.760, 0.874])	([0.000, 0.000], [0.712, 0.827])	([0.197, 0.197], [0.197, 0.197])

are determined according to PFSs as presented in Table 3. Then, the linguistic terms are converted to the corresponding interval-valued Pythagorean fuzzy numbers (Table 5). Then, the converted interval-valued Pythagorean numbers are aggregated according to Eq. (8) and shown in Table 6. Finally, the importance level of each criterion is determined according to the opinions of the four decision-makers. Similar operations are carried out within the sub-criteria, and the local and global weights of the main and sub-criteria are computed and illustrated in Table 7.

Table 7 Local and global weights the criteria

Criteria	Sub-criteria	Local weight	Global weight
*C*1 (0.280)	*C*11	0.403	0.113
	*C*12	0.597	0.167
*C*2 (0.084)	*C*21	0.415	0.035
	*C*22	0.585	0.049
*C*3 (0.332)	*C*31	0.444	0.147
	*C*32	0.286	0.095
	*C*33	0.270	0.089
*C*4 (0.272)	*C*41	0.343	0.093
	*C*42	0.657	0.179
*C*5 (0.032)	*C*51	0.292	0.009
	*C*52	0.708	0.022

4.3 Implementation of PFTOPSIS to specify green suppliers

The PFTOPSIS method is carried out by using the weights obtained from PFAHP to select the best supplier. The linguistic variables for the assessment of potential suppliers are defined by the Pythagorean fuzzy numbers that can be seen in Table 8. The decision-makers evaluated the suppliers from the use of linguistic terms, and the terms are transformed to Pythagorean fuzzy numbers according to the scale given in Table 8. Since the evaluations of the decision-makers are different, the four individual evaluations have been aggregated according to Eq. (9), and the aggregated decision matrix is given in Table 9.

After the Pythagorean fuzzy decision matrix is created in the PFTOPSIS method, PIS and NIS values are obtained, and the closeness coefficients are calculated and presented in Table 10. The priority order of the green supplier is $S4 > S2 > S3 > S5 > S1$: thus, $S4$ is the best green supplier.

Table 8 Pythagorean fuzzy linguistic ratings and Pythagorean fuzzy numbers

Linguistic term	Corresponding Pythagorean fuzzy number (u, v)
Very poor (VP)	(0.15, 0.85)
Poor (P)	(0.25, 0.75)
Medium poor (MP)	(0.35, 0.65)
Medium (M)	(0.50, 0.45)
Medium good (MG)	(0.65, 0.35)
Good (G)	(0.75, 0.25)
Very good (VG)	(0.85, 0.15)

Table 10 Closeness coefficients of suppliers

Suppliers	$D(x_i, x^+)$	$D(x_i, x^-)$	$\xi(x_i)$	Rank
$S1$	0.496	0.023	– 17.028	5
$S2$	0.035	0.497	– 0.198	2
$S3$	0.287	0.292	– 9.300	3
$S4$	0.029	0.490	– 0.014	1
$S5$	0.478	0.036	– 16.398	4

4.4 Sensitivity analysis

Sensitivity analysis is performed to test the results of the criterion weights. If the existing ranking order is changed when the weight of the criteria change, it can be said that the results obtained are in nature robust; otherwise, they are sensitive. In this context, ten different experimental sets were generated, the weights of the criteria were changed and the ranking results are given in Table 11.

Based on the results presented in Table 11, the place of the best supplier does not change when the weight of the first and third criteria is dominant (the sum of the two criteria is at least 0.60) and the ranking results are robust. On the other hand, if the weights of the second, fourth and fifth criterion are increased, the ranking of best supplier is changed and the ranking results are sensitive.

5 Results and conclusion

Companies must give importance to environmental competencies due to important environmental issues such as global warming, epidemics and demands from governments and consumers. The emergence of new technologies has led to changes in the purchasing and production processes, and exposed modification in the decision-making processes of companies. The purpose of this study is to investigate how the practices of Industry 4.0 technologies are integrated into the GSS problem. Many methods are presented to identify the best green supplier. In recent years, PFSs have emerged as an effective tool to depict the ambiguity of MCDM problems. PFSs are capable of expressing ambiguity and uncertainty in the opinions of decision-makers, and PFSs are more capable of addressing the uncertainty of real-life problems. For this reason, in this study, a new method for GSS has been proposed by considering Industry 4.0 applications under Pythagorean knowledge.

In the proposed approach, the evaluation criteria were determined by the experts of the case company, and the linguistic variables of Pythagorean fuzzy numbers were used in the evaluations of the experts. The weights of the evaluation criteria were determined by the interval-valued PFAHP method, and suppliers were evaluated by PFTOPSIS taking into account the distance and similarity between alternatives. Finally, a case study was executed to verify the feasibility of the proposed GSS approach.

Our case study results reveal that three different criteria, production, delivery and quality, are the most important factors from the Industry 4.0 window for GSS. These three criteria cover 88% of the total weight for GSS. Decision-

Table 9 Aggregated Pythagorean decision matrix

	$S1$	$S2$	$S3$	$S4$	$S5$
$C11$	(0.207, 0.798)	(0.587, 0.389)	(0.458, 0.557)	(0.679, 0.322)	(0.229, 0.774)
$C12$	(0.519, 0.463)	(0.830, 0.170)	(0.621, 0.365)	(0.830, 0.170)	(0.477, 0.526)
$C21$	(0.621, 0.365)	(0.807, 0.194)	(0.729, 0.272)	(0.830, 0.170)	(0.585, 0.397)
$C22$	(0.428, 0.598)	(0.830, 0.170)	(0.477, 0.526)	(0.750, 0.250)	(0.474, 0.570)
$C31$	(0.220, 0.795)	(0.652, 0.343)	(0.490, 0.508)	(0.729, 0.272)	(0.308, 0.703)
$C32$	(0.305, 0.698)	(0.750, 0.250)	(0.590, 0.423)	(0.750, 0.250)	(0.261, 0.747)
$C33$	(0.229, 0.774)	(0.707, 0.290)	(0.519, 0.463)	(0.743, 0.260)	(0.207, 0.798)
$C41$	(0.314, 0.695)	(0.763, 0.239)	(0.500, 0.450)	(0.705, 0.296)	(0.314, 0.695)
$C42$	(0.207, 0.798)	(0.707, 0.290)	(0.458, 0.557)	(0.652, 0.343)	(0.229, 0.774)
$C51$	(0.619, 0.373)	(0.830, 0.170)	(0.705, 0.296)	(0.830, 0.170)	(0.519, 0.463)
$C52$	(0.587, 0.389)	(0.850, 0.150)	(0.652, 0.343)	(0.807, 0.194)	(0.652, 0.343)

Table 11 Sensitivity analysis for different criterion weights on ranking results

Experiment no.	*S*1	*S*2	*S*3	*S*4	*S*5
1	−5.588	−0.712	−2.878	0.000	−5.943
2	−27.094	0.000	−21.302	−3.903	−26.672
3	−75.725	−7.621	−38.783	0.000	−70.753
4	−107.184	0.000	−61.631	−14.562	−102.183
5	−75.917	0.000	−55.128	−9.604	−71.237
6	−11.460	0.000	−6.760	−0.455	−11.071
7	−10.262	−0.233	−5.166	−0.006	−9.923
8	−9.481	0.000	−5.087	−0.049	−9.157
9	−9.275	0.000	−4.960	−0.076	−8.996
10	−9.340	−0.058	−4.825	−0.018	−9.037

makers want to increase their presence in the world market by offering quality products. Thus, these criteria take maximum weightage by decision-makers. Konya holds over 65% of the agricultural tools and machinery sector which is one of the important centers of Turkey in internal and external markets. According to the PFAHP results (Table 7), Quality 4.0, service level and IoT and CPS criteria obtained the most important sub-criterion in the assessment. In order to increase the efficiency of the lawnmowers production that keeps with 16% of the most produced agricultural tools and machinery, the production process must be carried out in high quality. Although techniques such as just-in-time, kaizen and six sigma are the main factors for quality (Sinha and Anand 2018), the importance of criteria change when we focus on industry 4.0 components. Implementing key components of Industry 4.0 leads to digitalization of the supplier selection process (Ghadimi et al. 2019). While companies have difficulty in developing products, optimizing production processes and using product usage data for their products, IoT technology enables to overcome these difficulties (Tao et al. 2016). Data collected from products, logistics operations and production processes help to improve products and services (Kamble et al. 2018). The fact that companies are ahead of the competition stems from the basic components of Industry 4.0. However, without the high and comprehensive quality management system in the use of new technologies, they will not be able to have the necessary qualifications for Industry 4.0 success.

As a result of this study, the dimensions that should be taken into consideration for the companies aiming to improve the supplier selection process in agricultural production enterprises are revealed through the Industry 4.0 window. Owing to the MCDM methods used in the study, it was aimed that decision-makers overcome uncertainty more easily. In future studies, the different criteria, which affect the purchasing process can be included, and the approach can be expanded and also can be applied for different sectors.

Authors' contributions All authors contributed extensively to the work presented in this paper.

Acknowledgements This research received no specific grant from any funding agency in the public, commercial or not-for-profit sectors.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Availability of data and material All data generated or analyzed during this study are included in this manuscript.

Code availability The authors confirm that the data supporting the findings of this study are available within the manuscript.

References

Angel M (2019) Quality 4.0: how to reduce cost of quality with Industry 4.0—Tulip. https://tulip.co/blog/quality/how-to-reduce-cost-of-quality-with-industry-4-0/. Accessed 1 Apr 2020

Banaeian N, Mobli H, Fahimnia B et al (2018) Green supplier selection using fuzzy group decision making methods: a case study from the agri-food industry. Comput Oper Res 89:337–347. https://doi.org/10.1016/J.COR.2016.02.015

Chen T, Lin Y-C (2017) Feasibility evaluation and optimization of a smart manufacturing system based on 3D printing: a review. Int J Intell Syst 32:394–413. https://doi.org/10.1002/int.21866

Chen Z, Ming X, Zhou T, Chang Y (2020) Sustainable supplier selection for smart supply chain considering internal and external uncertainty: an integrated rough-fuzzy approach. Appl Soft Comput 87:106004. https://doi.org/10.1016/J.ASOC.2019.106004

Das S, Das R, Tripathy BC (2020) Multi-criteria group decision making model using single-valued neutrosophic set. LogForum 16:421–429. https://doi.org/10.17270/J.LOG.2020.446

Demircan Keskin F, Kabasakal İ, Kaymaz Y, Soyuer H (2019) An assessment model for organizational adoption of Industry 4.0 based on multi-criteria decision techniques BT. In: Durakbasa NM, Gencyilmaz MG (eds) Proceedings of the international symposium for production research 2018. Springer, Cham, pp 85–100

Dev NK, Shankar R, Swami S (2019) Diffusion of green products in Industry 4.0: reverse logistics issues during design of inventory and production planning system. Int J Prod Econ. https://doi.org/10.1016/J.IJPE.2019.107519

Dutta A, Tripathy B (2016) On the class of p-absolutely summable sequence ℓi (p) of interval numbers. Songklanakarin J Sci Technol 38:143–146. https://doi.org/10.14456/sjst-psu.2016.19

Erdogan M, Ozkan B, Karasan A, Kaya I (2018) Selecting the best strategy for Industry 4.0 applications with a case study BT: industrial engineering in the Industry 4.0 era. In: Calisir F, Camgoz Akdag H (eds). Springer, Cham, pp 109–119

Ghadimi P, Wang C, Lim MK, Heavey C (2019) Intelligent sustainable supplier selection using multi-agent technology: theory and application for Industry 4.0 supply chains. Comput Ind Eng 127:588–600. https://doi.org/10.1016/J.CIE.2018.10.050

Govindan K, Rajendran S, Sarkis J, Murugesan P (2015) Multi criteria decision making approaches for green supplier evaluation and selection: a literature review. J Clean Prod 98:66–83. https://doi.org/10.1016/J.JCLEPRO.2013.06.046

Govindan K, Kadziński M, Sivakumar R (2017) Application of a novel PROMETHEE-based method for construction of a group compromise ranking to prioritization of green suppliers in food supply chain. Omega 71:129–145. https://doi.org/10.1016/J.OMEGA.2016.10.004

Gul M (2018) Application of Pythagorean fuzzy AHP and VIKOR methods in occupational health and safety risk assessment: the case of a gun and rifle barrel external surface oxidation and colouring unit. Int J Occup Saf Ergon. https://doi.org/10.1080/10803548.2018.1492251

Gul M, Ak MF (2018) A comparative outline for quantifying risk ratings in occupational health and safety risk assessment. J Clean Prod 196:653–664. https://doi.org/10.1016/J.JCLEPRO.2018.06.106

Gupta S, Soni U, Kumar G (2019) Green supplier selection using multi-criterion decision making under fuzzy environment: a case study in automotive industry. Comput Ind Eng 136:663–680. https://doi.org/10.1016/J.CIE.2019.07.038

Hasan MM, Jiang D, Ullah AMMS, Noor-E-Alam M (2020) Resilient supplier selection in logistics 4.0 with heterogeneous information. Expert Syst Appl 139:112799. https://doi.org/10.1016/J.ESWA.2019.07.016

Hashemi SH, Karimi A, Tavana M (2015) An integrated green supplier selection approach with analytic network process and improved Grey relational analysis. Int J Prod Econ 159:178–191. https://doi.org/10.1016/J.IJPE.2014.09.027

Hermann M, Pentek T, Otto B (2016) Design principles for industrie 4.0 scenarios. In: 2016 49th Hawaii international conference on system sciences (HICSS). pp 3928–3937

Ilbahar E, Karaşan A, Cebi S, Kahraman C (2018) A novel approach to risk assessment for occupational health and safety using Pythagorean fuzzy AHP & fuzzy inference system. Saf Sci 103:124–136. https://doi.org/10.1016/J.SSCI.2017.10.025

Jena MC, Mishra SK, Moharana HS (2020) Application of Industry 4.0 to enhance sustainable manufacturing. Environ Prog Sustain Energy 39:13360. https://doi.org/10.1002/ep.13360

Jiun-Shen LT, Le TP, Andrea G, Koh LS (2012) Using FAHP to determine the criteria for partner's selection within a green supply chain: the case of hand tool industry in Taiwan. J Manuf Technol Manag 23:25–55. https://doi.org/10.1108/17410381211196276

Kamble SS, Gunasekaran A, Gawankar SA (2018) Sustainable Industry 4.0 framework: a systematic literature review identifying the current trends and future perspectives. Process Saf Environ Prot 117:408–425. https://doi.org/10.1016/J.PSEP.2018.05.009

Karasan A, Ilbahar E, Cebi S, Kahraman C (2018) A new risk assessment approach: safety and critical effect analysis (SCEA) and its extension with Pythagorean fuzzy sets. Saf Sci 108:173–187. https://doi.org/10.1016/J.SSCI.2018.04.031

Küpper D, Knizek C, Ryeson D, Noecker J (2019) Quality 4.0 takes more than technology. https://www.bcg.com/publications/2019/quality-4.0-takes-more-than-technology.aspx. Accessed 1 Apr 2020

Lee AHI, Kang H-Y, Hsu C-F, Hung H-C (2009) A green supplier selection model for high-tech industry. Expert Syst Appl 36:7917–7927. https://doi.org/10.1016/J.ESWA.2008.11.052

Liang R, Chong H-Y (2019) A hybrid group decision model for green supplier selection: a case study of megaprojects. Eng Constr Archit Manag 26:1712–1734. https://doi.org/10.1108/ECAM-10-2018-0462

Liao C-N, Fu Y-K, Wu L-C (2016) Integrated FAHP, ARAS-F and MSGP methods for green supplier evaluation and selection. Technol Econ Dev Econ 22:651–669. https://doi.org/10.3846/20294913.2015.1072750

Liou JJH, Chuang Y-C, Zavadskas EK, Tzeng G-H (2019) Data-driven hybrid multiple attribute decision-making model for green supplier evaluation and performance improvement. J Clean Prod 241:118321. https://doi.org/10.1016/J.JCLEPRO.2019.118321

Liu B, De Giovanni P (2019) Green process innovation through Industry 4.0 technologies and supply chain coordination. Ann Oper Res. https://doi.org/10.1007/s10479-019-03498-3

Mathiyazhagan K, Sudhakar S, Bhalotia A (2018) Modeling the criteria for selection of suppliers towards green aspect: a case in Indian automobile industry. OPSEARCH 55:65–84. https://doi.org/10.1007/s12597-017-0315-8

Mishra AR, Rani P, Pardasani KR, Mardani A (2019) A novel hesitant fuzzy WASPAS method for assessment of green supplier problem based on exponential information measures. J Clean Prod 238:117901. https://doi.org/10.1016/J.JCLEPRO.2019.117901

Mousakhani S, Nazari-Shirkouhi S, Bozorgi-Amiri A (2017) A novel interval type-2 fuzzy evaluation model based group decision analysis for green supplier selection problems: a case study of battery industry. J Clean Prod 168:205–218. https://doi.org/10.1016/J.JCLEPRO.2017.08.154

Nascimento DLM, Alencastro V, Quelhas OLG et al (2019) Exploring Industry 4.0 technologies to enable circular economy practices in a manufacturing context: a business model proposal. J Manuf Technol Manag 30:607–627

Niesen T, Houy C, Fettke P, Loos P (2016) Towards an integrative big data analysis framework for data-driven risk management in Industry 4.0. In: 2016 49th Hawaii international conference on system sciences (HICSS), pp 5065–5074

Peng X, Yang Y (2016) Fundamental properties of interval-valued pythagorean fuzzy aggregation operators. Int J Intell Syst 31:444–487. https://doi.org/10.1002/int.21790

Qin J, Liu X, Pedrycz W (2017) An extended TODIM multi-criteria group decision making method for green supplier selection in interval type-2 fuzzy environment. Eur J Oper Res 258:626–638. https://doi.org/10.1016/j.ejor.2016.09.059

Ramirez-Peña M, Sánchez Sotano AJ, Pérez-Fernandez V et al (2020) Achieving a sustainable shipbuilding supply chain under I40 perspective. J Clean Prod 244:118789. https://doi.org/10.1016/J.JCLEPRO.2019.118789

Rouyendegh BD, Yildizbasi A, Üstünyer P (2020) Intuitionistic fuzzy TOPSIS method for green supplier selection problem. Soft Comput 24:2215–2228. https://doi.org/10.1007/s00500-019-04054-8

Sachdeva N, Shrivastava AK, Chauhan A (2019) Modeling supplier selection in the era of Industry 40. Benchmarking. https://doi.org/10.1108/BIJ-12-2018-0441

Santos K, Loures E, Piechnicki F, Canciglieri O (2017) Opportunities assessment of product development process in Industry 4.0. Procedia Manuf 11:1358–1365. https://doi.org/10.1016/J.PROMFG.2017.07.265

Satoglu S, Ustundag A, Cevikcan E, Durmusoglu MB (2018) Lean transformation integrated with Industry 4.0 implementation methodology BT—industrial engineering in the Industry 4.0 Era. In: Calisir F, Camgoz Akdag H (eds). Springer, Cham, pp 97–107

Sinha AK, Anand A (2018) Development of sustainable supplier selection index for new product development using multi criteria decision making. J Clean Prod 197:1587–1596. https://doi.org/10.1016/J.JCLEPRO.2018.06.234

Tao F, Wang Y, Zuo Y et al (2016) Internet of Things in product life-cycle energy management. J Ind Inf Integr 1:26–39. https://doi.org/10.1016/J.JII.2016.03.001

Tripathy BC, Das P (2012) On convergence of series of fuzzy real numbers. Kuwait J Sci Eng 39:57–70

Tripathy BC, Das PC (2019) On the class of fuzzy number sequences. Songklanakarin J Sci Technol 41:934–941

Tripathy BC, Debnath S (2013) On generalized difference sequence spaces of fuzzy numbers. Acta Sci Technol 35:117–121. https://doi.org/10.4025/actascitechnol.v35i1.15566

Turanoglu Bekar E, Skoogh A, Cetin N, Siray O (2019) Prediction of Industry 4.0's impact on total productive maintenance using a real manufacturing case BT. In: Durakbasa NM, Gencyilmaz MG (eds) Proceedings of the international symposium for production research 2018. Springer, Cham, pp 136–149

Ulutaş A, Topal A, Bakhat R (2019) An application of fuzzy integrated model in green supplier selection. Math Probl Eng 2019:4256359. https://doi.org/10.1155/2019/4256359

Uslu B, Eren T, Gür Ş, Özcan E (2019) Evaluation of the difficulties in the Internet of Things (IoT) with multi-criteria decision-making. Processes 7:164. https://doi.org/10.3390/pr7030164

Wang L, Törngren M, Onori M (2015) Current status and advancement of cyber-physical systems in manufacturing. J Manuf Syst 37:517–527. https://doi.org/10.1016/J.JMSY.2015.04.008

Wu Q, Zhou L, Chen Y, Chen H (2019) An integrated approach to green supplier selection based on the interval type-2 fuzzy best-worst and extended VIKOR methods. Inf Sci (Ny) 502:394–417. https://doi.org/10.1016/J.INS.2019.06.049

Xing K, Qian W, Zaman AU (2016) Development of a cloud-based platform for footprint assessment in green supply chain management. J Clean Prod 139:191–203. https://doi.org/10.1016/J.JCLEPRO.2016.08.042

Yager RR (2014) Pythagorean membership grades in multicriteria decision making. IEEE Trans Fuzzy Syst 22:958–965. https://doi.org/10.1109/TFUZZ.2013.2278989

Yazdani M, Chatterjee P, Zavadskas EK, Hashemkhani Zolfani S (2017) Integrated QFD-MCDM framework for green supplier selection. J Clean Prod 142:3728–3740. https://doi.org/10.1016/j.jclepro.2016.10.095

Yu Q, Hou F (2016) An approach for green supplier selection in the automobile manufacturing industry. Kybernetes 45:571–588. https://doi.org/10.1108/K-01-2015-0034

Yucesan M, Mete S, Serin F et al (2019) An integrated best-worst and interval type-2 fuzzy TOPSIS methodology for green supplier selection. Mathematics 7:182. https://doi.org/10.3390/math7020182

Zeng S, Chen J, Li X (2016) A hybrid method for pythagorean fuzzy multiple-criteria decision making. Int J Inf Technol Decis Mak 15:403–422. https://doi.org/10.1142/S0219622016500012

Zhang X, Xu Z (2014) Extension of TOPSIS to multiple criteria decision making with pythagorean fuzzy sets. Int J Intell Syst 29:1061–1078. https://doi.org/10.1002/int.21676