Green supplier selection in new era for sustainability: A novel method for integrating big data analytics and a hybrid fuzzy multi-criteria decision making

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Abstract
Environmentally conscious supplier selection has become increasingly important in recent years. Green supplier selection is one of the vital decisions of supply chain management, as it is preferred for businesses in the market that adopt an environmental approach and green philosophy in line with material and moral benefits. In this context, the problem of choosing the most efficient green supplier is addressed with a three-step methodology using big data analytics that includes an integrated approach and hybrid fuzzy AHP-TOPSIS techniques. First of all, big data plays an important role in delivering meaningful results by reducing complexity to a more fundamental level. It is possible to obtain more consistent results by examining a series of criteria in green supplier selection at a more reasonable and operational level. Thus, the role of big data analytics provides an input for decision-making, which enables a systematic reduction to more concise data. Then, these inputs are evaluated in a fuzzy environment with hybrid MCDM techniques and the most efficient green supplier is determined among the suppliers. This authentic study sheds light on providing a significant competitive advantage to businesses in line with their strategic targets as well as having environmental contributions to sustainability.
Keywords Green supplier selection · Big data analytics · Fuzzy decision making · Sustainability · Hybrid multi-criteria decision making

1 Introduction

The green supply chain has replaced the traditional supply chain management approach with the green approach and adoption of the green philosophy. The green supply chain is the process of incorporating green criteria or concerns into organizational purchasing decisions and long-term relationships with suppliers (İnce 2013; Zhao et al. 2017; Daddi et al. 2021). This article has addressed the green supplier selection which is one of the strategic decisions of green supply chain management. Green supplier selection is an important and complex problem for businesses that need to consider the effects of multiple options including multiple green criteria and subjective judgments at the same time within the framework of the green philosophy (Yazdani 2014; Kilic & Yalcin 2020; Micheli et al. 2020). Moreover, each one of these criteria is a chain of large amounts of data-based values that interact with each other.

This amount of data refers the big data which has a multi-dimensional characteristic. Laney (2001) was first introduced to literature three distinctive characteristics for big data, namely: volume, variety, and velocity. After, the dimensions of big data were extended as 5 V and 7 V, respectively. Figure 1 shows that 7 V dimensions of big data are characterized and analyzed in the conceptual framework. These dimensions have properties such as volume, velocity, variety, variability, veracity, visualization, and value. This conceptual framework aims to explain the multi-dimensional property of big data in a more understandable way, rather than one-dimensional.

From the scope of the big data working process, social networks, images, other information, and communication channels provide sources to it. Big data represents the voyage of a large volume of data from these sources transforms to value. The process is emphasized technological developments related to data storage, data processing, and data analytics that enable the likely to tackle exponential increments in data volume tendered in any structure of big data as time-saving (Schermann et al. 2014; Bag et al. 2020).

From this framework, big data analytics enables to provide uncover patterns, correlations, and other insights
from the large amounts of data. Big data analytics (BDA) refers to the use of analytical techniques to analyze large-volume and high-diversity data fast for the purpose of producing insight in decision-making (Liu et al. 2020; Wang et al. 2019). Especially, big data analytics enables faster and better decision-making with the speed of Hadoop and in-memory analytics.

Considering these beneficial effects of BDA, the importance of a data-driven supply chain increases (Li and Liu, 2019; Liu et al. 2020). In this sense, in this study, BDA plays an important role in making effective decisions in the complex and multi-criteria problem green supplier selection (GSS). BDA provides input that achieves a systematic reduction to more concise data for decision-making. Therefore, it allows obtaining meaningful results by reducing the existing complexity down to a more basic level.

In this study, green criteria were determined for GSS based on studies in the literature. After this, the frequency distributions of these criteria were measured by BDA. The first ten criteria were selected, starting with the criteria with the highest frequency distribution. Then, the suppliers were ranked by evaluating them in the fuzzy environment with hybrid multi-criteria decision-making (MCDM) techniques. The novelty of this study is that it covers an implementation with a hybrid framework that involves the problem of GSS that is accepted as one of the most important branches of supply chain management (SCM) and a trend in the world of SCM research, as well as quantitative and analytical calculation methods. Thus, we aimed to demonstrate the accuracy of the results and the more reliable capability of strategic goals with integrated big data analytics with the fuzzy MCDM approach based on two basic methodologies. This study is to analyze the proposed methodologies from the perspective of green supplier selection as well as to answer the following the research questions:

RQ1. What kind of a role does big data analytics have on the problem of green supplier selection?

RQ2. Why integrated MCDM approaches were used in the decision-making step of the green supplier selection?

RQ3. What are the effects of green criteria obtained from big data analytics on the selection of suppliers?

Keeping all these research questions in mind, the main purpose of this article is to select the most efficient green supplier with integrated fuzzy multi-criteria decision-making (MCDM) methodologies that consider human judgments, doubts, and uncertainties based on criteria determined by BDA. This study contributes to providing firms with GSS based on a fast algorithm of data-driven analysis and prioritization. Additionally, the analytics of a big data-driven approach can provide high profits for firms, and suppliers can become able to determine more guaranteed strategic goals for their future based on their current status (Badiezadeh et al. 2018; Javad et al. 2020). Thus, corporations should not ignore the benefits of big data
analytics which is seen as expensive or a waste of time (Roßmann et al. 2018; Dalić et al. 2020).

The remaining of this article was arranged as follows: In Sect. 2, the literature was reviewed by addressing the articles on green supplier selection within the scope of both content and methodology. In Sect. 3, the proposed hybrid fuzzy AHP-TOPSIS and big data analytics methodologies were addressed. In Sect. 4, the case study for a green supplier selection using the recommended methods was presented. In Sect. 5, the results were discussed. Finally, Sect. 6 includes the conclusion, managerial implications, the future research scope, and the limitations of this study were explained.

2 Literature review

The traditional problem of supplier selection has changed place with the green supplier selection with the increasing environmental sensitivity and awareness in the modern information and technological era. The literature was reviewed with the keywords “green supplier selection”, “big data analytics”, “green supply chain management”. Mainly, green supplier selection has increasingly become a trending issue for academia and practitioners. However, the number of articles that implement and realization big data analytics in the problem of supplier selection is limited and ignored. Therefore, this literature includes theoretical and practical articles that are based on the multi-directional benefits of big data in the supply chain and its usage purposes. Besides, we examined the literature review on green supplier selection based on the content and methodology of the studies in detail.

According to years, some articles in the literature are addressed the problem of green supplier selection as follows.

Lee et al. (2009) emphasized that as the environmental protection awareness of suppliers worldwide has increased, green production has become a substantial problem for producers. Using the Delphi technique, they determined criteria used for evaluating conventional and green suppliers. To obtain more consistent results by eliminating uncertainties like bias originating from the opinions of experts, they made assessments on supplier selection using the fuzzy AHP technique.

While selecting suppliers for a green supply chain (GSC), Lee et al. (2011) emphasized the most important factors in Taiwan’s economy with reference to the Taiwanese hand tool industry. As a result of an in-depth literature review, they examined criteria used in the evaluation of suppliers and significant effects with the proposed fuzzy AHP approach. Shen et al. (2013) underlined the importance of firms in terms of the effects of environmental sustainability on green policies in the context of increasing awareness on environmental protection, legislation, and global regulations. They produced an example for the problem of GSS with the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) in fuzzy settings that took into account the subjective judgments and uncertainties of humans.

Kannan et al. (2014) argued that the importance of GSC practices has increased with the increasing effectiveness of green practices in daily activities. They evaluated twelve suppliers using the TOPSIS method. They determined statistical differences using the Spearman rank-order correlation coefficient. They also used sensitivity analysis to investigate the effects of the decision-makers on supplier selection. This way, they aimed to raise awareness in supplier selection by determining high-priority criteria for GSS. Hashemi et al. (2015) proposed a comprehensive green supplier selection model problem using traditional criteria as well as economic and environmental criteria. With the Grey Relational Analytics (GRA) developed, green suppliers were evaluated by fuzzy ANP methods, which dealt with dependencies between criteria. Tang and Wei (2018) emphasized that due to environmental problems and ecological imbalance in China, businesses need to pay attention to the impact of their behavior on the environment in search of economic efficiency. Green supplier management has not been fully adopted in China compared to other countries. Several operators have been proposed with the generalized Pythagorean 2-double language in this context. Finally, an example of green supplier selection is implemented to prove the multi-featured decision-making process of the proposed algorithm.

Gupta et al. (2019) considered the positive effects of green supply chain management practices. They have assessed six suppliers under the umbrella of MCDM, which integrates three methodologies with “Multi-Attributive Border Approximation Area Comparison” (MABAC) noting that green supplier selection is based on traditional and mental criteria. The other three techniques are an integrated Fuzzy Analytic Hierarchy Process (FAHP), “Weighted Aggregated Sum-Product Assessment” WASPAS, and “Technique for order preference by similarity to ideal Solution” (TOPSIS) within the MCDM framework. Together with these methodologies and sensitivity analytics, they aim at the most efficient supplier selection. Liu et al. (2019) described the green supplier problem as a significant multi-criterion group decision making (MCGDM) problem that affects producer performance and efficiency. The validity and benefits of the proposed approach have been demonstrated by comparative analytics based on the MCGDM approach with the hesitant fuzzy priority weighted average (HFHPWA) operator.
As GSS became more popular, Wu et al. (2019) developed data envelopment analysis (DEA) by converting the implicit information in this problem into interval-valued Pythagorean fuzzy numbers (IVPFNs) with a Likert-type scale. With this method, they aimed to make the optimal decision for the evaluation and selection of green suppliers by also supporting their analysis with a numerical example.

For optimal GSS, Kilç and Yalçın (2020) proposed an integrated methodology that included Intuitionistic-Fuzzy TOPSIS (IF-TOPSIS) and a two-phase goal programming model. They emphasized that the proposed methodology provided an ambiguity-free setting for the decision-makers’ process of evaluation. Javad et al. (2020) stressed Green supply chain management considerable has occurred as a crucial approach for sustainability. They aim the selecting suppliers within the scope of green innovation ability for the Khouzestan Steel Company (KSC). They applied Fuzzy TOPSIS methodology to rank for suppliers. Moreover, they analyzed the key factors for supplier selection. They performed a sensitivity analysis to determine the limitations and potential strengths of their study. Gao et al. (2020) emphasized the importance of green suppliers to maintain a competitive advantage in electronics manufacturing enterprises. The researchers proposed a consensus-based group decision-making methodology that provided a dynamic and interactive model to help them in selecting the ideal green supplier. They reported that local revision strategies were easily covered by the methodology. They obtained results based on the ideal solution expressing the most important criterion and alternative. Đalić et al. (2020) presented the fuzzy PIPRECIA and interval rough simple additive weighting (SAW) methods for the assessment of supplier selection based on nine environmental criteria.

In the literature, BDA implementations for GSS are very rate. Nevertheless, there are some studies in the literature on “BDA” and “green supply chain management” (GSCM). Therefore, we observed that this limited literature included theoretical and applied research articles regarding the versatile benefits and usage objectives of big data in GSCM. Among relevant studies, the study by Zhao et al. (2017) proposed three objective optimization models in the context of green philosophy to increase efficiency in a green supply chain (GSC). For data entry into the optimization model, some data are removed by statistical analyses, and the suitable data are selected. Liu and Yi (2017) stated that, for a GSC in the big data environment in advertising, the green rating of products is also an important factor in influencing sales. In their study, four different game theories were proposed. For green suppliers, the study has a guiding role for advertising and pricing policies targeted in the big data environment. Liu et al. (2020) stressed the big data analytics (BDA) becomes increasingly considerable attention for the research world and practitioners on green supply chain management (GSCM). As a result of they contributed to the literature on BDA-enabled GSCM. Wang et al. (2020) explore the relationship between corporate social responsibility (CSR), green supply chain management, and firm performance, and consider the scope of big data analytics capability. As a recent study, Raut et al. (2021) investigate the role of big data analytics as a mediator between “sustainable supply chain business performance” and key factors, namely, lean practices, environmental practices, organizational practices, supply chain practices, social practices, financial practices, and total quality management.

According to the literature review in this study, due to the nature of the problem of GSS, MCDM techniques are more prevalently utilized. Furthermore, to obtain more consistent results in the problem of GSS, the problem is taken on with hybrid methods in fuzzy settings. Accordingly, Table 1 summarizes the classification of MCDM methodologies that have been used in GSS in the reviewed literature.

This article, which is presented to fill the gap in the literature on this particular topic, aims to select the most efficient green supplier systematically and effectively with hybrid MCDM approaches and BDA. Additionally, this study recommends fuzzy AHP-TOPSIS from among the MCDM techniques used in the case analysis. The scope and usage priorities of the methodologies are explained in detail in Sect. 3.

| Authors                  | Methodology Used                      | MCDM                          |
|--------------------------|---------------------------------------|-------------------------------|
| Lee et al. (2009)        | F-AHP                                 |                               |
| Lee et al. (2011)        | F-AHP HFPWA                           |                               |
| Shen et al. (2013)       | F-TOPSIS                              |                               |
| Hashemi et al. (2014)    | F-ANP                                 |                               |
| Kannan et al. (2014)     | F-TOPSIS                              |                               |
| Tang and Wei (2018)      | Pythagorean MADM                      |                               |
| Liu et al. (2019)        | MCGDM HFPWA                           |                               |
| Gupta et al. (2019)      | MABAC FAHP WASPAS TOPSIS              |                               |
| Wu et al. (2019)         | Interval-Valued Pythagorean F-AHP     |                               |
| Rouyendegh et al. (2020) | IF-TOPSIS                             |                               |
| Kilic and Yalcın (2020)  | IF-TOPSIS                             |                               |
| Javad et al. (2020)      | IF-TOPSIS                             |                               |
| Gao et al. (2020)        | GCDM                                  |                               |
| Đalić et al. (2020)      | F-PIPRECIA Interval Rough SAW         |                               |
3 Methodology

3.1 Big data analytics

Considering the volume, speed, diversity, and accuracy of BDA in the supply chain, as conventional statistical methods have become outdated, it has been important to investigate easily adaptable and effective statistical methods (Wang et al. 2016). BDA provides vital benefits in terms of increasing the operational efficiency in the supply chain. Its capacity to discover the potential market and provide information helps firms make better business decisions (Zhong et al. 2016).

The problem of green supply selection represents a complex but important problem involving a range of data in this study. The criteria used in the selection of green suppliers were determined from the articles in the literature filtered according to the aforementioned keywords. This filtering is related that the word frequency distribution has been used which is one of the applications of big data analytics. These criteria play a useful role in obtaining meaningful results with self-criteria by reducing the complexity to a more fundamental level with big data analytics. The frequency distribution of each criterion used in green supplier selection was determined by big data analytics. These criteria provide input for the criteria to be used in MCDM methods.

3.2 Multi-criteria decision making techniques (MCDM)

Supplier selection is a multi-criteria, complex supply chain problem. Therefore, MCDM methods, which are frequently used in supplier selection, evaluate a set of alternatives based on more than one feature and then select the best alternative (Rashidi and Cullinane 2019). In this scope, this is why we aim to choose the best efficient green supplier with fuzzy integrated MCDM approaches that take into account human judgment, doubts, and uncertainties according to the criteria determined. For this purpose, two MCDM methodologies proposed are fuzzy AHP & TOPSIS.

Fuzzy AHP method is based on the principle of operating the administrative decision mechanism by giving relative importance values to alternatives and criteria in complex decision problems. Fuzzy AHP method enables to decision makers the complex problems of to model in a hierarchical structure that clarifies the relationship between the main objective, criteria, sub-criteria, and alternatives of the problem (Sirisawat & Kiatcharoenpol 2018; Ligus & Peternek 2018). The most important characteristic of fuzzy AHP method is that can include both objective and subjective thoughts of the decision maker in the decision process. Fuzzy AHP method provides the decision-making process systematic and ensures the more accurate decisions. This method facilitates the applications by allowing the decision maker to correctly determine decision maker preferences regarding the target. In this scope, fuzzy AHP is preferred methodology that is applied well-known and frequently, powerful multi-criteria decision-making method developed to solve complex problems (Parung et al. 2018). Considering the advantages of fuzzy AHP, the weights of criteria were determined in this study. After weighing the criteria with fuzzy AHP, the alternatives were listed with the fuzzy TOPSIS method. When compared to other MCDM methodologies, TOPSIS encompasses superiorities in terms of bilateral benchmarking and which can tackle best and worst values (Yousefzadeh et al. 2020). Fuzzy TOPSIS is one of the most frequently used methods due to both these advantages and its capability of wide application area. Together with these advantages, under the fuzzy environment, AHP-TOPSIS methodologies were recommended and applied in the case study. The detailed steps of the methodologies are as follows:

![Fig. 2 A membership function of the triangular fuzzy number](https://example.com/figure2)

### Table 2 Linguistic rating and fuzzy number

| Linguistic Term (Criteria) | Fuzzy Triangular Number |
|---------------------------|-------------------------|
| Very Low (VL)             | (1,1,3)                 |
| Low (L)                   | (1,3,5)                 |
| Medium (M)                | (3,5,7)                 |
| High (H)                  | (5,7,9)                 |
| Very High (VG)            | (7,9,9)                 |
3.2.1 Fuzzy set theory

For the first time in 1965, Zadeh emphasized that the concept of fuzzy logic stems from the misconceptions and uncertainties caused by human language, judgment, and assessments (Valmohammadi and Dashti 2016). His work became a starting point with the publication of “Fuzzy Sets” in the “Information and Control Journal” for the solution of technical problems. In fuzzy logic, 1 and 0 are seen as boundaries, not absolute values. The members in the fuzzy set receive values in this range. The membership function of a triangular fuzzy number is shown in Eq. (1) (Banaeian et al. 2018).

\[ \mu(x) = \begin{cases} 0, & x < 1 \\ \frac{m-x}{m-r}, & 1 \leq x \leq m \\ \frac{r-x}{r-m}, & m \leq x \leq r \\ 1, & x > r \end{cases} \]  

(1)

Triangular fuzzy numbers are used as the membership function, which is illustrated in Fig. 2:

3.2.2 Fuzzy AHP

The analytical hierarchy process (AHP) method, first proposed by Saaty (1980), is one of the multi-criteria decision-making methods (Buckley 1985). This method is used that can choose from a large number of alternatives and where more than one decision-maker can take part situated in the process. Moreover, this method can be easily applied even in very complex problems due to the fact that it takes into account both quantitative and qualitative factors and is simple and useful (Göksu & Güngör, 2008). Fuzzy AHP method steps are defined as follows (Torfi et al. 2010).

Step 1. Fuzzy triangular numbers indicate the importance levels of the criteria relative to each other by expert decision-makers. Very Low (VL), low (L), medium (M), high (H), and very high (VH) scale in Table 2 has been used to express with five-dimensional linguistic ratios (Awasthi et al. 2018). The elements of the created hierarchy are compared in pairs. The purpose of the created comparison matrix is to determine the relative priority of the elements on the next higher level over each element. A decision matrix consisting of a fuzzy set is created.

\[ \tilde{A}^k = \begin{bmatrix} d_{11}^k & d_{12}^k & \cdots & d_{1n}^k \\ d_{21}^k & d_{22}^k & \cdots & d_{2n}^k \\ \vdots & \vdots & \ddots & \vdots \\ d_{n1}^k & d_{n2}^k & \cdots & d_{nn}^k \end{bmatrix} \]  

(2)

Step 2. The geometric mean of each column in the pairwise comparison matrix is found, it is divided by all elements in the column, and the normalized pairwise comparison matrix (R) is obtained.

\[ R = \left[ \begin{array}{c} \tilde{d}_{11} \\ \vdots \\ \tilde{d}_{nn} \end{array} \right] \]  

(3)

\[ \tilde{r}_i = \left( \prod_{j=1}^{n} \tilde{d}_{ij} \right)^{1/n}, i = 1, 2, \ldots, n \]  

(4)

Step 3. The criterion weights vector (w) is calculated by taking the arithmetic mean of all elements in each row of the normalized pairwise comparison matrix.

\[ \tilde{w}_i = \tilde{r}_i \otimes (\tilde{r}_1 \oplus \tilde{r}_2 \oplus \tilde{r}_3 \oplus \ldots \oplus \tilde{r}_n)^{-1} \]  

= (lwi, mwi, uwi).

Step 4. For each criterion, defuzzification is applied to the fuzzy weight values.

\[ M_i = \frac{lw_i + mw_i + uw_i}{3} \]  

(5)

Step 5. As the last step, the defuzzified values are normalized.

\[ N_i = \frac{M_i}{\sum_{i=1}^{n} M_i} \]  

(6)

3.2.3 Fuzzy TOPSIS

The TOPSIS method that was developed by Yoon and Hwang allows the selection of the alternative with the smallest distance to the positive and negative ideal
solutions (Ara 2015). In the TOPSIS algorithm the quantitive criteria are scaled using their own real numbers and for representation of the imprecision of spatial data, and human cognition over the criteria of the theory of linguistic variables is used. The fuzzy TOPSIS method which aims to solve multi-criteria decision-making problems under a fuzzy environment and to eliminate ambiguities in decision-makers of evaluations and keep biases to a minimum is more convenient than the traditional TOPSIS method (Sirisawat and Kiatcharoenpol 2018). The method offers the opportunity to obtain effective outputs as a result of simple process steps. In this respect, this MCDM technique is frequently used in supplier selection problems. Fuzzy TOPSIS method steps are defined as follows (Torfi et al. 2010; Banaeian et al. 2018). The linguistic variable scale in Table 3 was used to rate the criteria (Banaeian et al. 2018).

Step 1. Construct the fuzzy decision-making matrice.
MCDM problem includes a group of k decision-makers (D1,D2, ...s,Dk) containing m alternatives (A1,A2, ...,Am) and n criteria (C1,C2,...,Cn). In a group of k decision-makers, the criterion values of the alternatives are calculated as follows:

\[ x_{ij} = \frac{1}{K} \left[ x_{ij} + x_{ij}^2 + \ldots + x_{ij}^K \right] \]  

(8)

Step 2. \( \tilde{x}_{ij} \) (\( \forall i, j \)) ve \( \tilde{w}_j \) (j = 1,2,...,n) are linguistic triangular fuzzy numbers \( A_1,A_2,\ldots,A_m \) alternatives; \( K_1,K_2,\ldots,K_n \) decision criteria. \( x_{ij} = K_j \) shows that the fuzzy criterion value of the \( A_i \) alternative relative to the \( K_j \) criterion and the fuzzy significance weight of the \( \tilde{w}_j = K_j \) criterion.

These linguistic variables can be expressed with triangular fuzzy numbers \( \tilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij}) \) and \( \tilde{w}_j = (a_{j1}, b_{j2}, c_{j3}) \). The matrix D is called the fuzzy decision matrix and the matrix W is called the fuzzy weights matrix.

\[
\begin{bmatrix}
A_1 & x_{11} & x_{12} & \ldots & x_{1n} \\
A_2 & x_{21} & x_{22} & \ldots & x_{2n} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
A_m & x_{m1} & x_{m2} & \ldots & x_{mn} \\
\end{bmatrix}
\]

(9)

Step 3. Normalize the fuzzy decision matrix obtained from the fuzzy decision matrix.

\[ \tilde{R} = [\tilde{r}_{ij}]_{mn} \]

Step 4. Construct the fuzzy decision matrix which is normalized to the weight of criteria.

\[ \tilde{V} = [\tilde{V}_{ij}]_{mn} \]

(11)

Step 5. Calculate the fuzzy positive ideal solution and fuzzy negative ideal solution of criteria.

\[ A^+ = (\widetilde{V}_{1}, \widetilde{V}_{2}, \ldots, \widetilde{V}_{n}) \] positive ideal solution.

\[ A^- = (\widetilde{V}_{1}, \widetilde{V}_{2}, \ldots, \widetilde{V}_{n}) \] negative ideal solution.

The distances of fuzzy positive and negative ideal solutions for alternatives are calculated as follows:

\[ d_i^+ = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_{ij}^+), \quad i = 1, 2, \ldots, m \]

(12)

\[ d_i^- = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_{ij}^-), \quad i = 1, 2, \ldots, m \]

Step 6 Calculate the similarities to the ideal solution.

\[ \text{CC}_i = \frac{d_i^-}{d_i^+ + d_i^-}, \quad i = 1, 2, \ldots, m \]

(14)

Step 7. Rank the preference order. Choose an alternative with maximum \( \text{CC}_i \) or rank alternatives according to \( \text{CC}_i \) in descending order.

4 Case study

In this study, four different electronics industry suppliers were evaluated by three expert decision-makers to the problem of choosing the most efficient green supplier. Linguistic evaluations were made by making necessary interviews with the experts. Besides, detailed information of experts is given in Table 4.

The case study consists of two main parts. In the first section, with BDA, the criteria to be used in GSS are
determined. The second part covers the application of methodologies for multi-criteria decision-making methods used to evaluate suppliers. Green suppliers were evaluated using integrated AHP-TOPSIS methodologies in the fuzzy environment from MCDM methods.

### 4.1 Big data analytics

Dataset consisting of all of the articles from different sources is used to calculate the frequency keywords and keyword groups’ distribution (bigrams and trigrams) automatically in this part. This dataset refers to criteria related to green supplier selection articles. The big data analytics is derived from a textual analytics based on the word frequency distribution of the articles in the literature. In this regard, a total of 79 criteria used for the selection of green suppliers are identified. Evaluating all criteria for suppliers makes the problem more difficult and complex. In this scope, it is important to know the frequency of these ngrams to classify and represent the articles and also the domain. Premade ngram list is provided by the authors of the chapter. The criter name and the representation of the total number of scanned articles are as follows:

- ("[criter name]", count)
- The ngram list is presented below:
- ("[cost"]", 2576),
- ("[quality"]", 1922),
- ("[flexibility"]", 248),
- ("[environmental", 'management', 'system"]", 61),
- ("[speed"]", 39),
- ("[green", 'production']", 29),
- ("[green", 'technology']", 21),
- ("[after", 'sales', 'service']", 18),
- ("[innovativeness"]", 17),
- ("[delivery", 'reliability']", 17),
- ("[green", 'logistics']", 14),
- ("[on", 'time', 'delivery']", 14),
- ("[cleaner", 'technology']", 13),
- ("[biodiversity"]", 12),
- ("[performance", 'history']", 11),
- ("[dependability"]", 11),
- ("[reduce", 'reuse', 'recycling']", 10)
- ("[donations"]", 10),
- ("[global", 'risks']", 10),
- ("[direct", 'cost']", 9),
- ("[labour", 'practices']", 7),
- ("[design", 'for', 'environment']", 7),
- ("[greenhouse", 'gas', 'emission']", 6),
- ("[defect", 'ratio']", 6),
- ("[job", 'opportunities']", 6),
- ("[financial", 'capability']", 5),
- ("[decent", 'work']", 5),
- ("[local", 'communities']", 5),
- ("[economic", 'growth']", 5),
- ("[resource", 'allocation']", 5),
- ("[green", 'development']", 4),
- ("[energy", 'conservation']", 4),
- ("[materials", 'energy']", 4),
- ("[green", 'packing']", 4),
- ("[reuse", 'recycling']", 4),
- ("[quality", 'of', 'relationship']", 4),
- ("[supplier", 'social', 'selection']", 4),
- ("[labour", 'health']", 4),
- ("[social", 'commitment']", 4),
- ("[environmental", 'selection', 'procedure']", 3),
- ("[legal", 'compliance']", 3),
- ("[staff", 'development']", 3),
- ("[ethical", 'issues']", 2),
- ("[worker", 'dismissal']", 2),
- ("[currency", 'risk']", 2),
- ("[effectiveness", 'of', 'communication']", 1),
- ("[safety", 'system']", 1),
- ("[job", 'safety']", 1),
- ("[desire", 'for', 'business']", 1),
- ("[products", 'quality', 'improvement']", 1),
- ("[indirect", 'cost']", 1),
- ("[safety", 'audit', 'assessment']", 1),
- ("[product", 'responsibility']", 1),
- ("[buyer", 'supplier', 'constraints']", 1),
- ("[economic", 'welfare']", 1),
- ("[e-commerce", 'capability']", 1),
- ("[vocational", 'health']", 1),
- ("[information", 'revelation']", 1),
- ("[worker", 'safety']", 1),
- ("[economical", 'welfare']", 1),
- ("[local", 'communication', 'influence']", 1),

| Expert   | Title                                      | Education                      | Years of experience |
|----------|--------------------------------------------|--------------------------------|---------------------|
| E1       | Logistics and Supply Chain Coordinator     | PhD in Industrial Engineering  | 19                  |
| E2       | Supply Chain Management Business Analyst   | Masters in Process Engineering | 13                  |
| E3       | Purchasing and Supply Chain Manager        | Masters in Industrial Engineering | 11              |
The system is implemented in Python programming language and the Pseudo code is as follows:

1. INITIALIZE dictionary named total_count_dict with 0's as values and keywords as keys.
2. FOR each_file in folder:
   - DEFINE dictionary named count_dict
   - INITIALIZE count_dict with 0's as values and keywords as keys
   - EXTRACT textual data from each_file
   - CLEAN the textual data from punctuations
   - LOWERCASE all the words and TOKENIZE textual data
   - CALCULATE bi_grams and TOKENIZE
   - CALCULATE tri_grams and TOKENIZE
   - FOR each_key in keywords:
     - IF number of words in each_key is equal to 1
       - FOR each_token in tokenized textual data
         - IF each_key is in each_token
           -INCREMENT count_dict[each_key]
           -INCREMENT total_count_dict[each_key]
     - IF number of words in each_key is equal to 2
       - FOR each_token in tokenized bi_grams
         - IF each_key is in each_token
           -INCREMENT count_dict[each_key]
           -INCREMENT total_count_dict[each_key]
     - IF number of words in each_key is equal to 3
       - FOR each_token in tokenized tri_grams
         - IF each_key is in each_token
           -INCREMENT count_dict[each_key]
           -INCREMENT total_count_dict[each_key]
   - PRINT name of each_file and count_dict
   - PRINT total_count_dict

Table 5 Results of the total count of each criterion

| Criteria                                      | Count |
|----------------------------------------------|-------|
| Cost (C1)                                    | 2576  |
| Quality (C2)                                 | 1922  |
| Speed (C3)                                   | 39    |
| Flexibility (C4)                             | 248   |
| After-sales service (C5)                     | 18    |
| Green Production (C6)                        | 29    |
| Green Technology (C7)                        | 21    |
| Green Logistics (C8)                         | 14    |
| Reduce, Reuse, Recycling(3R) (C9)            | 10    |
| Environmental Management System (C10)        | 61    |

The code is implemented to be used as a simple console program. Basically, it uses the provided ngram list as input to search through a folder consisting articles. To be able to correctly search through the article there should be some pre-processing to be done prior. This includes making everything lowercase (including ngrams which is also
provided to the system as a simple text file), removing punctuations, and removing new lines. Lastly, bigrams and trigrams are created as well as unigrams. After that, the same tokenization steps are also applied to the keyword file as well to maintain homogeneous data type. At the end, we have a list of tokenized ngrams for wanted keywords and also tokenized ngrams of the data to be searched through. When the code is executed it produces detailed report of the frequency of ngrams from keyword file for each article and also for all files in total. The ten criteria with the highest frequency distribution according to the results are shown in Table 5.

4.2 Multi-criteria decision making applications

The criteria were determined by the big data analytics and evaluated using MCDM techniques in the second part of the case study.

4.2.1 Fuzzy AHP application

Step 1. For each criterion, a decision matrix (DM) determined by linguistic variables as in Table 6 was created.

Step 2. The geometric mean values of the values in the normalized decision matrix are presented in Table 7.

Step 3. The priority weight of each criterion was calculated as shown in Eq. 4 and is presented in Table 8.

The criterion weights found by using the fuzzy AHP method were used to rank the suppliers in the fuzzy TOPSIS method.

4.2.2 Application of fuzzy TOPSIS

Step 1. The decision matrix formed using linguistic variables is shown in Table 9.

Step 2. After filling in the numerical values corresponding to the linguistic variables, the min, and max ideal values for each criterion are shown in Table 10.

Step 3. The distance of each alternative from the positive ideal solution and the negative ideal solution was calculated and is shown in Table 11.

Step 4. The coefficient index was calculated for each alternative and presented in Table 12.

Step 5. Ranking the alternatives.

The suppliers which are ranked by the coefficient index are shown in Fig. 3.

4.3 Sensitivity analyses

Sensitivity analytics provide to see the limits and potential of the suppliers according to the changing conditions. The
analytics was carried out to detect the effects of possible changes in the weights of the criteria in determining the most efficient green supplier in this study. The boundary of the study and the situations in which the performance of suppliers constitute the initial coefficient values that may be affected are taken comprehensively by sensitivity analytics.

For this purpose, ten different experimental sets were applied. The high value (0.9, 0.9, 0.9) was given to the weight of relevant criterion in each condition and the other nine criteria were remained constant considering to initial coefficient index. To give an example, Condition 1 represents the change in Criterion 1 (C1) which is given the value (0.9, 0.9, 0.9) and other criteria were tackled as a constant. The changes are applied to each green criteria, respectively, and the new coefficient index for suppliers was recorded. Figure 4 demonstrates the results of the sensitivity analysis of how the ranking of the green

### Table 7: The geometric mean of fuzzy comparison values of criteria

|   | C1   | C2   | C3   | C4   | C5   | C6   | C7   | C8   | C9   | C10  |
|---|------|------|------|------|------|------|------|------|------|------|
| ri | 2,786,403 | 4,419,429 | 5,906,678 | 1,316,074 | 1,848,148 | 2,817,313 | 273,276 | 287,913 | 316,474 | 289,434 |
|   | 1,316,074 | 1,848,148 | 2,817,313 | 273,276 | 287,913 | 316,474 | 289,434 | 287,913 | 316,474 | 289,434 |
|   | 2,786,403 | 1,316,074 | 1,848,148 | 2,817,313 | 273,276 | 287,913 | 316,474 | 289,434 | 287,913 | 316,474 |
|   | 5,906,678 | 2,817,313 | 2,817,313 | 273,276 | 287,913 | 316,474 | 289,434 | 287,913 | 316,474 | 289,434 |

### Table 8: The importance weight of the criteria

|   | C1   | C2   | C3   | C4   | C5   | C6   | C7   | C8   | C9   | C10  |
|---|------|------|------|------|------|------|------|------|------|------|
| Wi | 0.202,009 | 0.450,267 | 0.95,798,584 | 0.095,413 | 0.188,296 | 0.45,693,132 | 0.019,812 | 0.034,844 | 0.07,797,133 | 0.016,161 |
|   | 0.016,161 | 0.02,926 | 0.07,253,219 | 0.016,629 | 0.032,243 | 0.09,436,208 | 0.020,983 | 0.056,332 | 0.10,327,627 | 0.018,503 |
|   | 0.013,362 | 0.033,915 | 0.07,897,790 | 0.018,503 | 0.044,792 | 0.11,015,462 | 0.021,948 | 0.063,307 | 0.14,137,598 | 0.022,184 |
|   | 0.022,184 | 0.066,744 | 0.14,354,970 | 0.020,009 | 0.450,267 | 0.95,798,584 | 0.095,413 | 0.188,296 | 0.45,693,132 | 0.019,812 |

### Table 9: Linguistic evaluation data of alternatives

|   | Cost(C1) | Quality(C2) | Speed(C3) | Flexibility(C4) | After-sales service (C5) | Green Production(C6) | Green Technology(C7) | Green Logistics(C8) | Environmental Management System(C10) |
|---|----------|-------------|-----------|-----------------|--------------------------|----------------------|----------------------|----------------------|--------------------------------------|
| DM1 | S1 | G | MG | P | F | F | MP | P | F | MP | F |
| DM2 | S2 | MG | MG | G | MG | F | MG | F | MG | F | MG |
| DM3 | S3 | MG | MP | F | G | MG | MP | MG | G | MG | MP |
| DM4 | S4 | MG | MP | MP | MP | F | MG | MP | MG | MP | MG |

### Figure 4: Sensitivity Analysis Results
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suppliers is affected according to changing the weight of the criteria.

According to the results of scenario analysis, three different situations were observed in the ranking of the suppliers.

The effect of the change in Cost (C1), Quality (C2), and Green Logistics (C8) criteria has the same result on the suppliers and is ranked as \( S1 > S3 > S4 > S2 \). When the weight of these criteria was increased, S2 gain importance in regard to S4 and was positioned more preferable. These criteria provide a more significant effect for S2.

The effect of the change in Speed (C3), Green Technology (C7), After-sales service (C5), and Environmental Management System (C10) criteria has the same result on suppliers and is ranked as \( S3 > S1 > S4 > S2 \). Mainly, when are tackled only the after-sales service (C5) criterion, S1 and S3 seem to the nearly almost equal coefficient index value. However, S3 is ranked as up-front. The change in the weight of these criteria positively affected S3 and thus it ranked among the foremost in the competitive market.

The effect of the change in Flexibility (C4), Green Production (C6) and Reduce, Reuse, Recycling (3R) (C9) criteria has the same result on suppliers and is ranked as \( S1 > S3 > S4 > S2 \). The ranking remained the same considering the initial solution. The notable change in the weight of these criteria does not make a difference on the suppliers. As a result, the effects of these criteria on green supplier selection are more negligible compared to other criteria.

### 4.4 Scenario analyses

Scenario analyses are provided to see the limits and potential of the suppliers in this study. Each scenario is based on the initial coefficient values. The boundary of the study and the situations in which the performance suppliers constitute the initial coefficient values that may be affected are taken in comprehensively by scenario analytics. These are examined in terms of sensitivities on initial ranking based on changing linguistic terms on decision-makers on certain criteria.

#### 4.4.1 Scenario 1: Sensitivity to changes in linguistic term of decision makers for the environmental management system criterion (C10)

In this scenario, two different conditions are analyzed for decision-makers(DM). First, in Scenario 1a, the linguistic evaluations of DM2 and DM3 for the environmental management system criterion of Supplier 2 have been improved. Linguistic evaluation of DM1 remained constant. DM2 changed to “Fair” and DM3 to “Medium
Table 13 Coefficient index according to Scenario 1a

| C10 | DM1 | DM2 | DM3 |
|-----|-----|-----|-----|
| F   | F   | MG  |
| S1  | 0.810,382,035 |     |     |
| S2  | 0.164,333,922 |     |     |
| S3  | 0.645,978,759 |     |     |
| S4  | 0.164,053,717 |     |     |

Fig. 4 Results of the Sensitivity Analyses

Table 14 Coefficient index according to Scenario 1b

| C10 | DM1 | DM2 | DM3 |
|-----|-----|-----|-----|
| F   | MG  |     |
| S1  | 0.811,095,195 |     |     |
| S2  | 0.178,037,761 |     |     |
| S3  | 0.671,805,578 |     |     |
| S4  | 0.185,966,021 |     |     |

Fig. 6 Coefficient index according to Scenario 1b

Table 15 Coefficient index according to Scenario 2

| C8  | DM1 | DM2 | DM3 |
|-----|-----|-----|-----|
| G   | G   | G   |
| S1  | 0.776,560,355 |     |     |
| S2  | 0.143,043,714 |     |     |
| S3  | 0.671,805,578 |     |     |
| S4  | 0.185,966,021 |     |     |

Fig. 7 Coefficient index according to Scenario 2
Good”. According to the obtained results, even if the coefficient index is equal, Supplier2 outperformed Supplier4 with a slight difference and enabled a change in the final ranking. The results are shown in Table 13 and Fig. 5.

Secondly, in Scenario 1b, the evaluations of DM2 and DM3 are considered as “Medium Good”. According to the results, Supplier 2 obtained a better coefficient index than Supplier 4 with a more significant difference. The results are shown in Table 14 and Fig. 6.

According to the scenario results, a little improvement for the environmental management system criterion for Supplier2 enabled Supplier4 to get ahead. For this purpose, Supplier2 should improve the Environmental Management System which encompasses a set of processes that provides a firm to reduce its environmental impacts and increase its operating efficiency. Thus, Supplier2 could take place in better conditions in the competitive market.

4.4.2 Scenario 2: Sensitivity to changes in linguistic term of decision makers for the green logistics criter(C8)

In this scenario, the linguistic evaluations of DM2 and DM3 for Supplier3’s green logistics criteria have been increased. DM2 remained constant. DM1 changed to DM3 “Good”. According to the results, there was no change in the final ranking. With the improvement in the green logistics criteria, Supplier3 has a more effective result, however, this is not sufficient for the final ranking. Supplier3 should make enhancements by taking the other nine criteria into account in order to be at the forefront of the competitive market. The results are shown in Table 15 and Fig. 6.

4.4.3 Scenario 3: Sensitivity to changes in linguistic term of decision makers for the green logistics criter(C8) and Reduce, Reuse, Recycling(3R) (C9)

In this scenario, the linguistic analyses of the DMs were changed for two different criteria. The analyses of DM2 were kept unchanged. The DM1 and DM3 linguistic rankings for the “green logistics (C8)” and “reduce, reuse, recycle (3R)” criteria of Supplier3 were taken as “Very Good”. According to the results, Supplier3 had a closer performance index to that of Supplier1, but it did not show a performance as good as that of Supplier1 (Fig. 7). Although the improvement in the “green logistics (C8)” and “reduce, reuse, recycle (3R)” criteria made the performance of Supplier 3 better, it did not cause a change in the final ranking. Therefore, Supplier 3 should make changes by considering the other eight criteria. The results are shown in Table 16 and Fig. 8.

5 Result and discussion

In this study, four different electronics industry suppliers were evaluated according to the green criteria. The green criteria to be used in supplier selection were determined with big data analytics among many criteria. According to the results obtained with the fuzzy TOPSIS method using the weights obtained from the fuzzy AHP method, Supplier1 and Supplier3 have higher values of 0.797637 and 0.604464, respectively. On the other hand, Supplier2 and Supplier4 are by far lower with coefficient index values of 0.125232 and 0.346852, respectively. According to the results obtained in Fig. 7, it is seen that green suppliers are listed as S1 > S3 > S4 > S2 in the environmental dimension of sustainability. This situation can be turned into opportunities that create a competitive advantage for suppliers.

It can be said that Supplier1 and Supplier3 adopt green production, technology, and logistics activities since they are more efficient green suppliers. Additionally, it can be said that these suppliers act in accordance with environmental management systems and implement 3R (Reduce, Reuse, Recycle) circular economy strategies for their businesses. Since these suppliers are more environmentally friendly, sensitive, and conscious, they can be preferred more than other suppliers in the competitive market. Thus, they can also bring high profits to their businesses besides contributing to environmental sustainability.
Supplier2 and Supplier4 need to develop their strategies from an environmental point of view to take part in the competitive market. They should adopt and implement the environmental management system as a corporate culture in their businesses. They need to address the green approach in all activities of the supply chain from production to logistics. Moreover, recycling-oriented activities contribute to their businesses both environmentally and economically. Therefore, Supplier2 and Supplier4 should not ignore these contributions to the future of their business.

Green suppliers also provide indispensable value for the environmental dimension, which is an indispensable condition for sustainability. In this regard, environmentally conscious green suppliers, which are becoming more important every day, will be the reason to be preferred more than other suppliers.

6 Conclusion

Environmentally conscious supplier selection has become increasingly important in recent years. Thus, this article contains an integrated approach to achieve the goal of the most efficient green supplier selection problem. This study also uses a fuzzy approach within the proposed three-step methodology. The use of fuzzy MCDM techniques with big data analytics addresses the green supplier selection problem from a different perspective beyond the traditional understanding. The proposed methodology has been applied to the problem of selecting the most efficient green supplier on four different electronics industry suppliers, including three expert decision-makers. First of all, it is possible to obtain more consistent results with big data analytics by examining the green supplier selection, which is a problem related to a series of criteria, complex and strategic decisions, at a more reasonable and operational level. The ten most frequently used (frequency distribution) criteria in the selection of green suppliers among the articles scanned with big data analytics were determined by big data analytics. The weight of each criterion was determined using fuzzy AHP. Benchmark weights were then compared by three supply experts using the fuzzy TOPSIS method. The results are more accurate within the framework of fuzzy logic, which takes human doubts, judgments, and uncertainties into account. In addition, the ranking of suppliers is also related to the 7 V dimensions of big data that raise awareness to provide a competitive advantage to suppliers. The dimensional approach enables having a better understanding of green criteria compared to the conceptual framework. The fact that the green supplier selection problem was addressed both with big data analytics and hybrid fuzzy MCDM methods shows that this is an authentic study that contributes to the literature. The problem of green supplier selection contributes to sustainability as well as provides a significant competitive advantage to businesses in line with their strategic goals.

6.1 Managerial Implications

This study focused on the effects of the green supplier selection problem on the performance of chain stakeholders of suppliers in the electronics industry. Thus, the results obtained from the study can be a guide for both supply chain practitioners and academics. This study determined the green criteria with big data analytics and evaluated four suppliers based on these criteria. The efforts of companies to select green suppliers and their investments in this direction can be effective in increasing their competitiveness.

Therefore, we consider the following implications to be important in managerial approaches:

- Since the top management is responsible for the development and planning of environmental policies, the results of this study can be evaluated by senior executives.
- Thanks to the approach we propose in this article, companies can seize significant improvement opportunities in terms of environmental sustainability.
- The suppliers, who have adopted the green philosophy and consider environmental sustainability, can be determined with the proposed approach in the selection process of the suppliers.
- Fuzzy AHP and TOPSIS hybrid methodology can be used to monitor companies’ environmental sustainability performance and make comparisons in this direction.
- Green criteria may differ between sectors. Therefore, the criteria obtained from big data analytics can be considered in a broader or narrower framework.
- The results of the approach focused in this study were obtained in line with the opinions of decision-makers. So, each company can manage its own evaluation and decision-making process with its own evaluation process.
- It is necessary to consider environmental sustainability to gain a competitive advantage in the modern world market where environmentally conscious businesses are preferred. Senior executives can take their place in the leading position in the market by developing strategies in this context.
6.2 Limitations and Future Scope

Although this was a comprehensive study, it also had limitations that need to be guided for future studies. One of the main limitations of this study is that it only focused on fuzzy AHP and fuzzy TOPSIS methods. It might be useful to evaluate green suppliers with other methods in addition to these methods. Additionally, this study focused on the electronics industry. There might be different green criteria that affect the environmental dimension of the sustainability of each industry. In this regard, green suppliers can be evaluated in different industries.

Additionally, this article is suitable for implementations in various supplier selection problems. It can be applied in the evaluation of multiple suppliers in problems that contain multi-dimensional, complex, and comprehensive data set, such as the problem of sustainable supplier selection. According to the results obtained, the relationships between all dimensions of sustainability can be discussed. Besides, this study weighted decision-makers personally. Future studies can weight decision-makers based on their experiences and knowledge.

Declarations

Conflict of interest No potential conflict of interest was reported by the authors.

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