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Assessment of Vacuum Cleaner Motors with F-AHP-PROMETHEE II

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Abstract

The effectiveness and efficiency of vacuum cleaners largely depend on the performance of their motors. As the core component, a motor's power, durability, and energy consumption directly impact the overall functionality of the vacuum cleaner. Selecting the right motor is thus crucial to meeting consumer expectations and maintaining a competitive edge in the market. Ranking vacuum cleaner motor alternatives is a complicated multiple criteria decision making (MCDM) problem since it involves various potentially competing qualitative and quantitative criteria. In this study, a MCDM approach is presented for the assessment of vacuum cleaner motors for a company of electric motors in Turkey. Here, first fuzzy Analytic Hierarchy Process (F-AHP) is utilized to determine criteria weights and then, fuzzy Preference Ranking Organization Method for Enriching Evaluations II (F-PROMETHEE II) is applied to determine the ranking of vacuum cleaner motor alternatives, using these weights. 12 maximization criteria are determined with the help of 3 managers/coordinators of the electric motors company acting as decision makers (DMs) in the process to assess 4 vacuum cleaner motor alternatives.

Keywords
MCDM, fuzzy AHP, fuzzy PROMETHEE II, vacuum cleaner motor selection.

1. Introduction
In today's rapidly advancing technological landscape, the efficient performance and sustainability of household appliances such as vacuum cleaners are of paramount importance. For Senur Elektrik Motorları San. ve Tic. A.Ş., commonly referred to as Senur, a leading electric motors company in Turkey, selecting the best motor alternative to meet consumer demands for higher efficiency, lower energy consumption, and greater reliability is crucial. Founded in 1962, Senur has significantly advanced the small electrical household appliances sector in Turkey and has been instrumental in enhancing the country’s international standing in this industry.

This study aims to evaluate various vacuum cleaner motor alternatives specifically for Senur, utilizing a fuzzy MCDM method, F-AHP-PROMETHEE II. By incorporating fuzzy logic into the MCDM framework, this research addresses the inherent uncertainties and subjective judgments involved in the decision-making process. The findings of this study will provide valuable insights for Senur, enabling the company to make informed and effective choices in the selection of vacuum cleaner motors that align with contemporary demands for performance and sustainability.

In this research, for assessment of vacuum cleaner motor alternatives, F-AHP and F-PROMETHEE II are combined to have both methods’ advantages. F-PROMETHEE II method is easy to apply with stable results (Moradpour et al. 2011; Velasquez and Hester 2013; Samanlioglu and Ayağ 2016, 2017, 2020; Burak et al. 2022), however it does not provide an instruction to calculate criteria weights. Therefore, a method such as F-AHP is needed to calculate criteria weights beforehand. On the other hand, utilizing F-AHP for both assessment of criteria and ranking of alternatives (without the integration with F-PROMETHEE II) can be burdensome due to large number of pairwise comparisons (Samanlioglu and Ayağ 2017, 2020; Burak et al. 2022, Samanlioglu et al. 2024). Hence, in this research the integration of both methods, namely F-AHP-PROMETHEE II is utilized. In F-AHP-PROMETHEE II, first, F-AHP is implemented to compute criteria weights and then F-PROMETHEE II is applied to rank vacuum cleaner motor alternatives, utilizing the acquired weights.

2. Literature Review

AHP (Saaty 1980) is a MCDM method with "multi-level and hierarchical structure". In AHP, pairwise comparison of criteria are made to determine criteria weights and then pairwise comparisons of alternatives with respect to each criterion are realized to determine alternative scores, and finally these scores are aggregated for ranking alternatives. Fuzzy version of AHP, F-AHP (Van Laarhoven and Pedrycz 1983) is studied vastly in the literature. A bibliometric analysis of F-AHP is presented in Castelló-Sirvent et al.'s research (Castelló-Sirvent et al. 2022) and a survey about integration of F-AHP with other methods and recent developments are given in Kahraman et al.'s studies (Kahraman et al. 2020, 2022).

PROMETHEE, developed by Brans (Brans 1982), is a "family of outranking methods". Details about (fuzzy) PROMETHEE with various versions and applications can be acquired in Samanlioglu and Ayağ's research (Samanlioglu and Ayağ 2017). In this research, F-AHP and F-PROMETHEE II is applied to capture the "ambiguity and fuzziness of DMs' judgements" with the concepts of "fuzzy set theory" (Lootsma 1997; Zadeh 1965, 1994). Different fuzzy versions of PROMETHEE along with comparison with other MCDM methods were given in Yatsalo et al.'s research (Yatsalo et al. 2021). F-PROMETHEE was recently used in several applications such as assessments of urinary tract infection diagnostic techniques (Abobakr et al. 2023), "3D filaments used in additive manufacturing of biomedical tools" (Ozsahin et al. 2023), strategies towards a "Cross-Country Renewable Energy Cooperation" (Papapostolou et al. 2024), and public transport modes (Oubahman and Duleba 2024), etc.

In the literature, integration of F-AHP with F-PROMETHEE II (F-AHP-PROMETHEE II) was applied to various different MCDM problems such as evaluation of milling machines (Dağdeviren 2008), tasks of assignments (Avikal et al. 2013), solar power plants (Samanlioglu and Ayağ 2017), market risks for river cruises (Zhu et al. 2021), smartphone models (Goswami and Behera 2021), and irrigation methods (Burak et. al. 2022), etc. The closest research to this study were by Kumar and Singh (2020), Yang et al. (2024) and Kumcu et al. (2024). Kumar and Singh (2020) implemented Technique for Order Preference by Similarity to Ideal Solutions (TOPSIS) to evaluate vacuum cleaners, where they used equal criteria weights. Yang et al. (2024) utilized fuzzy analytic network process (FANP) and decision-making trial and evaluation laboratory (DEMATEL) to examine the significant factors that affects users in buying a robot vacuum. Kumcu et al. (2024) applied Pythagorean F-AHP to determine criteria weights and then Pythagorean Fuzzy TOPSIS to assess new generation vacuum cleaner types. To the best of authors' knowledge, in the literature, there is no MCDM research paper that focuses on vacuum cleaner motor assessment. The main motivation of this research is to provide a systematic methodology to potential practitioners and readers.

3. F-AHP-PROMETHEE II Method

A "fuzzy number" is a special "fuzzy set" $F = \{(x, \mu_F(x)), x \in R\}$ where x is a real number, $R: -\infty < x < +\infty$ and $\mu_F(x)$ is from R to [0, 1]. In this research, "triangular fuzzy numbers (TFN)" are applied due to its easiness in F-AHP-PROMETHEE II. A TFN, $\tilde{M} = (l, m, u)\ \ l \le m \le u$ has the "triangular type membership function";

$$\mu_F(x) = \begin{cases} 0 & x < l \\ (x-l)/(m-l) & l \le x \le m \\ (u-x)/(u-m) & m \le x \le u \\ 0 & x > u \end{cases} \quad (1)$$

Arithmetic operations with TFNs are previously given in several research papers (Wu et al. 2016; Samanlioglu and Ayağ 2020). If $\tilde{B} = (l, m, u)$ is a positive TFN, $\tilde{B}$ can be defuzzified with "graded mean approach" as (Kwong and Bai 2003; Yong 2006; Samanlioglu et al. 2024):

$$B = (l + 4m + u)/6 \quad (2)$$

In F-AHP-PROMETHEE II, k number of DMs do pairwise comparison of criteria utilizing the linguistic terms presented in Table 1 (Samanlioglu and Ayağ 2020; Ayağ and Samanlioglu 2021) and also evaluate each alternative with respect to each criterion with the linguistic terms in Table 2 (Samanlioglu and Ayağ 2020; Ayağ and Samanlioglu 2021). These DM evaluations are converted to TFNs and taking the average of TFNs of k DMs, "aggregated fuzzy pairwise comparison matrix of criteria" ($\widetilde{A}$) (based on pairwise evaluation of n criteria) in F-AHP and "aggregated fuzzy decision matrix" ($\widetilde{D}$) (based on evaluation of m alternatives with respect to n criteria) in F-PROMETHEEII are determined.

Table 1. Evaluation scale for criteria in F-AHP-PROMETHEE II

Linguistic terms	Triangular fuzzy number (TFN)
Absolutely strong (AS)	(2, 5/2, 3)
Very strong (VS)	(3/2, 2, 5/2)
Fairly strong (FS)	(1, 3/2, 2)
Slightly strong (SS)	(1, 1, 3/2)
Equal (E)	(1, 1, 1)
Slightly weak (SW)	(2/3, 1, 1)
Fairly weak (FW)	(1/2, 2/3, 1)
Very weak (VW)	(2/5, 1/2, 2/3)

Table 2. Evaluation scale for alternatives in F-AHP-PROMETHEE II

Linguistic terms	Triangular fuzzy number (TFN)
Very poor (VP)	(0,0,1)
Poor (P)	(0,1,3)
Medium poor (MP)	(1,3,5)
Fair (F)	(3,5,7)
Medium good (MG)	(5,7,9)
Good (G)	(7,9,10)
Very good (VG)	(9,10,10)

In F-AHP-PROMETHEE II, at first, F-AHP (Samanlioglu and Ayağ 2017, 2020; Samanlioglu et al. 2024) is utilized to calculate criteria weights. Elements of $\widetilde{\boldsymbol{A}}$ matrix is defuzzified with Eq. (2) and the defuzzified nxn "pairwise comparison matrix" A is determined. Crisp weights $\boldsymbol{w} = (\boldsymbol{w_1}, \boldsymbol{w_2}, \dots, \boldsymbol{w_n})$ are obtained by taking the average of the elements on each row of normalized $\boldsymbol{A}$. So the "normalized principal eigen vector" is $\boldsymbol{w}$. From $\boldsymbol{Aw} = \boldsymbol{\lambda_{\max} w}$, the "principal eigen value" ($\boldsymbol{\lambda_{max}}$) is determined and the "consistency index" (CI) is calculated as:
$\boldsymbol{CI} = (\boldsymbol{\lambda_{max}} - \boldsymbol{n})/(\boldsymbol{n} - \boldsymbol{1})$. Afterwards, "consistency ratio" (CR) is obtained as $CR=CI/RI$, where RI is "random index". If the $CR < 0.10$, the comparison is "consistent", otherwise it is not (Saaty, 1980).

In F-AHP-PROMETHEE II, after the calculation of weights, F-PROMETHEE II (Yuen and Ting 2012; Samanlioglu and Ayağ 2017, 2020; Burak et al. 2022) is applied to rank alternatives. Elements of $\widetilde{\boldsymbol{D}}$ matrix is defuzzified with Eq. (2) and D matrix is determined with crisp $\boldsymbol{r_{ij}}$ values. "Aggregated preference indices" are calculated where $\boldsymbol{P_j}(\boldsymbol{A_i}, \boldsymbol{A_k}) = \boldsymbol{P_j}\big(\boldsymbol{d}(\boldsymbol{A_i}, \boldsymbol{A_k})\big) = \boldsymbol{P_j}\big(\boldsymbol{r_{ij}} - \boldsymbol{r_{kj}}\big)$ is a "preference function" showing how much DM prefers $\boldsymbol{A_i}$ to $\boldsymbol{A_k}$ with respect to criterion j. "Gaussian criterion" was selected from the generalized functions and this is generally chosen specifically when there is continuing data in applications. Here, the preference function is:

$$P(d) = \begin{Bmatrix} 0 & d \le 0 \\ 1 - e^{-\frac{d^2}{2s^2}} & d > 0 \end{Bmatrix} \text{ for maximization criteria} \quad (3)$$

$$P(d) = \begin{Bmatrix} 0 & d \ge 0 \\ 1 - e^{-\frac{d^2}{2s^2}} & d < 0 \end{Bmatrix} \text{ for minimization criteria} \quad (4)$$

"Aggregated preference index" $\pi(A_i, A_k)$ shows the degree of how much DM prefers A_i to A_k with respect to all the criteria. The "aggregated preference indices" are calculates as:

$$\pi(A_i, A_k) = \frac{\sum_{j=1}^{n} P_j(A_i, A_k).w_j}{\sum_{j=1}^{n} w_j}, \forall A_i, A_k \in A \; and \; i \ne k. \quad (5)$$

Afterwards, the "outranking flows" are obtained to rank the alternatives. Each alternative A_i faces (m-1) other alternatives in A. The "positive outranking flow" shows how A_i outranks other:

$$\emptyset^{+}(A_i) = \sum_{k=1}^{m} \pi(A_i, A_k) \tag{6}$$

The "negative outranking flow" indicates how A_i is outranked by others:

$$\emptyset^{-}(A_i) = \sum_{k=1}^{m} \pi(A_k, A_i) \tag{7}$$

The "net outranking flow" is calculated as:

$$\emptyset(A_i) = \emptyset^{+}(A_i) - \emptyset^{-}(A_i), \qquad \forall\, i \in \{1, \dots, m\} \tag{8}$$

The "net outranking flow" is utilized to rank the alternatives from best to worst where the alternative with the highest $\emptyset(A_i)$ is the best. (Yuen and Ting 2012, Samanlioglu and Ayağ 2017, 2020; Burak et al. 2022)

4. Application and Results

A case study of Senur Company is presented where 4 vacuum cleaner motor candidates (A1,…,A4) are assessed with respect to 12 maximization criteria (C1,…,C12) by 3 DMs. The DMs from Senur Company are the R& D manager (DM1), the quality assurance manager (DM2) and the purchasing coordinator (DM3). 12 maximization criteria are: Vacuum Power (C1), powder pulling force (C2), suction power (C3), speed range (C4), capacity (C5), run time of the motor (C6), future expectation (C7), cost efficiency (C8), ergonomical compatibility (C9), torque (C10), efficiency (C11), and airflow (C12). Vacuum cleaner motor alternatives that are going to be ranked from best to worst are: Domel vacuum motor (A1), KingClean vacuum motor (A2), Cinderson vacuum motor (A3), and Yongji vacuum Motor (A4).

In F-AHP-PROMETHEE II, at first, 3 DMs make pairwise evaluations of criteria with the linguistic terms in Table 1 as seen in Table 3. They are converted to TFNs with the scale in Table 1 and averaging these TFNs of 3DMs, the "aggregated fuzzy pairwise comparison matrix of criteria" $\tilde{A}$ is attained. Defuzzifying $\tilde{A}$ with Eq. (2), defuzzified "aggregated pairwise comparison matrix" A in Table 4 is obtained. Criteria weights $w = (w_1, w_2, \dots, w_n)$, determined by taking the average of the elements on each row or normalized A, are also given in Table 4. With $Aw = \lambda_{\max} w$, the "principal eigen value" is determined as $\boldsymbol{\lambda_{max}}$=12.889, so "consistency index" is $CI = (12.889 - 12)/(12 - 1)$ =0.081. *RI*=1.48 when *n*=12, so "Consistency ratio" is computed as *CR*=*CI*/*RI*=0.081/1.48=0.0546. Since *CR*=0.0546 < 0.10, the comparison is "consistent".

Table 3. Pairwise comparison of criteria by 3 DMs

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
C1	E,E, E	AS,VS,E	AS,VS,E	AS,FS,E	AS,FS,E	AS,SW,E	AS,FS,E	VS,SW,E	AS,VW,E	AS,SE,E	SW,AW,E	AS,AW,E
C2		E,E,E	E,VS,E	VS,FS,E	VS,VS,E	VS,SW,E	VS,FS,E	SS,SW,E	AS,VW,E	AS,SW,E	VW,SW,E	AS,AW,E
C3			E,E,E	FS,FS,E	FS,FS,E	FS,FS,E	FS,FS,E	SS,SW,E	VS,VW,E	VS,SW,E	AW,SW,E	AS,AW,E
C4				E,E,E	VW,FW,E	E,FW,E	E,FW,E	VW,FW,E	E,VW,E	VW,SW,E	AW,VW,E	E,VW,E
C5					E,E,E	SW,E,E	E,SW,E	AW,FW,E	E,VW,E	FW,SW,E	AW,E,E	E,VW,E
C6						E,E,E	SS,VS,E	AW,SS,E	SS,VW,E	E,SW,E	AW,E,E	SS,VW,E
C7							E,E,E	AW,SS,E	E,SW,E	SW,SW,E	AW,VS,E	E,VW,E
C8								E,E,E	AS,SW,E	AS,SW,E	SW,VS,E	AS,VW,E
C9									E,E,E	E,VW,E	AW,SW,E	E,VW,E
C10										E,E,E	AW,VS,E	E,VW,E
C11												

Table 4. Defuzzified aggregated pairwise comparison matrix *A* and obtained weights of criteria (*w*)

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	*w*
C1	0.096	0.149	0.139	0.100	0.108	0.102	0.111	0.119	0.095	0.107	0.088	0.102	0.110
C2	0.061	0.081	0.101	0.090	0.108	0.091	0.100	0.091	0.095	0.107	0.074	0.102	0.092
C3	0.061	0.068	0.076	0.080	0.086	0.092	0.089	0.091	0.083	0.095	0.071	0.102	0.083
C4	0.067	0.060	0.060	0.060	0.048	0.062	0.060	0.066	0.060	0.059	0.058	0.066	0.060
C5	0.067	0.055	0.060	0.090	0.065	0.068	0.066	0.063	0.060	0.064	0.073	0.066	0.066
C6	0.080	0.070	0.060	0.070	0.066	0.069	0.091	0.075	0.062	0.070	0.073	0.068	0.071
C7	0.067	0.057	0.060	0.070	0.066	0.057	0.067	0.075	0.070	0.070	0.103	0.066	0.069
C8	0.083	0.082	0.076	0.090	0.108	0.102	0.099	0.090	0.106	0.107	0.119	0.105	0.097
C9	0.109	0.092	0.088	0.080	0.086	0.091	0.069	0.075	0.071	0.059	0.071	0.066	0.080
C10	0.080	0.068	0.065	0.082	0.077	0.071	0.070	0.075	0.095	0.070	0.103	0.066	0.077
C11	0.102	0.111	0.115	0.110	0.097	0.104	0.089	0.078	0.109	0.096	0.091	0.116	0.101

Afterwards, in F-AHP-PROMETHEE II, DMs evaluate alternatives with respect to each criterion using the linguistic terms in Table 2 as seen in Table 5. They are converted to TFNs with the scale in Table 2 and averaging these TFNs of 3DMs, the "fuzzy evaluation matrix" $\tilde{D}$ is attained. Defuzzifying $\tilde{D}$ with Eq. (2) and the defuzzified "decision matrix" D in Table 6 is attained. "Gaussian criterion" is selected for the criteria and "aggregated preference index matrix" for the alternatives is presented in Table 7. Utilizing the "aggregated preference indices", the "positive, negative and net outranking flows" are obtained as in Table 8. Alternatives are ranked with the "net outranking flows" and the ranking is also presented in Table 8. As a result, with F-AHP-PROMETHEE II, the ranking of alternatives from best to worst is KingClean vacuum motor (A2), Domel vacuum motor (A1), Cinderson vacuum motor (A3), and Yongji vacuum Motor (A4). The best alternative is determined as KingClean vacuum motor (A2) since it has the highest "net outranking flow".

Table 5. 3 DMs' assessments of the alternatives with respect to each criterion by 3 DMs

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
A1	G,G,VG	F,G,VG	G,G,VG	F,G,G	F,G,G	F,G,VG	MP,G,F	P,MG,VP	F,G,G	F,G,G	MG,G,G	F,G,VG
A2	MG,G,VG	F,G,VG	MG,G,VG	F,G,MG	F,G,G	F,MG,MG	MP,G,F	MP,MG,F	F,G,G	F,G,G	F,G,G	F,G,VG
A3	MG,MG,VG	F,MG,VG	MG,MG,VG	F,G,MG	F,MG,G	F,MG,G	F,G,F	F,MG,P	F,G,G	F,G,G	MG,MG,G	F,G,VG

Table 6. Decision matrix *D*

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
A1	9.167	7.889	9.167	7.556	7.389	7.889	5.611	2.778	7.556	7.556	8.222	7.889
A2	8.556	7.889	8.556	6.944	7.556	6.333	5.611	5.000	7.556	7.556	7.556	7.889
A3	7.944	7.278	7.944	6.944	6.944	6.944	6.278	4.389	7.556	7.556	7.611	7.889

Table 7. Aggregated preference index matrix

	A1	A2	A3	A4
A1	0	0.006	0.009	0.015
A2	0.009	0	0.003	0.004
A3	0.006	0.001	0	0.002
A4	0.010	0.001	0.001	0

Table 8. Outranking flow indices and rank

Alter.	A1	A2	A3	A4
$\emptyset^+$	0.030	0.017	0.008	0.012
$\emptyset^-$	0.024	0.008	0.014	0.021
$\emptyset$	0.005	0.008	-0.005	-0.009
Rank	2	1	3	4

5. Conclusion

In this paper, F-AHP-PROMETHEE II is applied to assess vacuum cleaner motor alternatives for a electric motors company in Turkey, Senur. Initially, criteria importance weights are calculated with F-AHP and next employing these weights, F-PROMETHEE II is executed to rank motor alternatives. Presently, in the literature, there is no research paper that targets assessment of vacuum cleaner motors with a MCDM method. Employment of fuzzy numbers in F-AHP-PROMETHEE II mirrors the ambiguity and uncertainty of assessments of DMs and integration of F-AHP and F-PROMETHEE II reflects the benefits of both methods.

F-AHP-PROMETHEE II ranking results are presented to the company and suggestions are made towards the best vacuum cleaner motor alternative, KingClean Vacuum Motors (A2). As future research, "inner/outer dependence", "feedback", and "correlation" relations between criteria can be taken into account and FANP and correlated F-AHP can be applied and these methods can also be integrated to F-PROMETHEE II for numerous MCDM problems.

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