v1: 2 July 2024

Research Article

Refrigerant Selection in Air Conditioning Systems Considering Thermodynamic, Environmental, and Economic Performance Using the BHARAT-II Multi-Attribute Decision-Making Method

Peer-approved: 2 July 2024

Qeios, Vol. 6 (2024)
ISSN: 2632-3834

Ravipudi Venkata Rao[1], Ravipudi Jaya Lakshmi[2]

1. Sardar Vallabhbhai National Institute of Technology, Sūrat, India; 2. University of Virginia, Charlottesville, United States

A simple and effective multi-attribute decision-making method, named as "Best Holistic Adaptable Ranking of Attributes Technique (BHARAT)-II", to choose the best refrigerant for air conditioning systems is presented. The thermodynamic properties of the refrigerants, and their environmental, and economic performances are also considered for the selection. Two case studies are provided to demonstrate the proposed multi-attribute decision-making method. The first case study addresses the problem of selecting the best refrigerant for residential split air conditioners out of 15 alternative refrigerants considering 12 selection attributes; the second case study addresses the problem of selecting the best refrigerant for automobile air conditioning systems by considering 14 alternative refrigerants and 13 selection attributes. The results of the proposed decision-making method are compared with those of other well-known multi-attribute decision-making methods such as EDAS, TOPSIS, and MOORA. The proposed method is shown to be simple to implement, providing a logical way for allocating weights to the selection attributes and is useful to solve the best alternative refrigerant selection problems of the residential as well as industrial refrigeration and air conditioning.

Corresponding author: Ravipudi Venkata Rao, ravipudirao@gmail.com

1. Introduction

Selecting the right refrigerant is crucial and essential to keep refrigeration and air conditioning systems operating at peak efficiency while keeping greenhouse gas pollution low. A suitable candidate for a refrigerant must possess the proper thermodynamic properties such as higher values of critical temperature, thermal conductivity, latent heat, vapor density, etc. and lower values of critical pressure, saturated pressure, liquid density, viscosity of liquid, environmental suitability characteristics such as lower ozone depletion potential (ODP), global warming potential (GWP), safety aspects such as lower flammability and toxicity, and economic aspects such as lower cost per kg of the refrigerant. The constraints indicated above make choosing a refrigerant more challenging and necessary for precise usage. At the moment, experimental methods and theoretical modelling are used to classify the refrigerants; this is an expensive and time-consuming operation. These challenging problems should be resolved by applying recent advancements in multi-attribute decision-making (MADM) methodologies that provide optimal solutions even in the presence of thermodynamic, environmental, and economic considerations (Souayeh et al., 2022). All these requirements are considered as the refrigerant selection attributes. As a number of refrigerants are available in the market, selecting the right refrigerant for a particular application becomes difficult and challenging. No single refrigerant can possess all the required properties and characteristics and hence selection of a best refrigerant for a given residential or industrial refrigeration and air conditioning application is considered as a MADM problem.

Any MADM method for refrigerant selection involves the (i). refrigerant alternatives, (ii). refrigerant selection attributes, (iii). weights of importance assigned to the refrigerant selection attributes, and (iv). performance data of the refrigerants corresponding to the selection attributes. The chosen MADM method process the given data keeping in view of these four components and suggests the best refrigerant for the given application for optimal performance. The person making the decision (known as decision-maker) considers the importance of each selection attribute for the particular application based on his/her expertise and professional judgment.

Recently, researchers have started using a few MADM methods to establish reliable methodologies for selecting the best refrigerants for certain applications. Souayeh et al. (2022) used different MADM methods like TOPSIS (technique for order preference by similarity to ideal solution), MOORA (multi-objective optimization of ratio analysis) [6,7], and EDAS (evaluation based on distance from average solution) for selection of best suitable eco-friendly refrigerants for HVAC sector and renewable energy devices. Entropy method was used for obtaining the weights of the attributes. Prabakaran et al. (2022) used EDAS method combined with entropy method for analyzing the performance of 15 refrigerants keeping lower GWP in view for residential air conditioning systems. The performance of each refrigerant was analyzed thermodynamically and compared their results with R22. Poongavanam et al. (2022) described how optimizing performance studies were measured on the selection of low GWP refrigerants for automobile air conditioning to obey the environmental protocols with the MADM methods of EDAS, TOPSIS, and MOORA.

Ustaoglu et al. (2022) analyzed vapor compression refrigeration cycle using advanced exergetic approach with Taguchi and ANOVA optimization and refrigerant selection with enviro-economic concerns by TOPSIS analysis. Singh et al. (2023) described the applications of different MADM methods such as TOPSIS, VIKOR (višekriterijumsko kompromisno rangiranje), grey relational analysis (GRA), and simple additive weighing (SAW) method, for refrigerant selection in domestic applications.

It is observed from the literature review on refrigerant selection that the researchers used different MADM methods like TOPSIS, EDAS, MOORA, VIKOR, GRA, and SAW. For obtaining the weights of importance of the refrigerant selection attributes, the entropy method and the AHP (analytic hierarchy process) method were used by the researchers and those weights were utilized in the MADM methods for processing the data.

Although the above-mentioned MADM methods are useful, they also have drawbacks. For example, the TOPSIS approach necessitates extensive computations that become more difficult as the number of alternatives and attributes increases. The ranks of alternatives provided by the TOPSIS method can vary depending on the different normalization techniques applied to standardize the data. In the case of VIKOR method, there is additional processing needed. The method could lead to different outcomes for the same attribute weights in different ranking lists depending upon the weight allotted to "the majority of attributes". The other MADM techniques have drawbacks of their own and require a significant amount of processing (Rao, 2024a; Rao, 2024b). The weights of the refrigerant selection attributes decided by the decision-maker are called the subjective weights. The AHP method (Saaty, 2007) generates a large number of comparison matrices by comparing attributes and alternatives on a scale from 1 to 9. The issue of contradictory judgements occasionally comes up. Furthermore, the way the weights are determined can affect the choice results. The weights of the refrigerant selection attributes can also be determined using objective approaches by utilizing methods like the entropy method. These weights are called the objective weights since the decision-maker has no control over how they are determined. Recently, Rao (2024a, 2024b, 2024c) developed BHARAT-II (Best Holistic Adaptable Ranking of Attributes Technique-II) method based on simple ranking procedure. The method is extended here and applied for refrigerant selection in different refrigeration and air conditioning applications. The objectives of the present work are as given below.

1. To apply the BHARAT-II method to decide the weights of importance of the refrigerant selection attributes for a given air conditioning system application.
2. To demonstrate and validate the applicability of BHARAT-II method to the selection of right refrigerants in air conditioning systems considering thermodynamic, environmental, and economic performances.

The proposed decision-making methodology is explained in detail in the next section.

2. Proposed BHARAT-II decision-making methodology for a given application

The following is a *general description* of the steps of the proposed BHARAT-II decision-making methodology for selection problems.

Step 1: Determine the pertinent selection attributes *Si* (*i = 1, 2,... m*), and the alternatives *Aj* (for *j = 1, 2,... n*) for the given selection problem. The selection attributes can be beneficial (i.e., higher values are desired) and non-beneficial (i.e., lower values are desired).

Step 2: Decide the order of importance of the selection attributes to obtain the weights w_i (for *i = 1, 2,..., m*). The order of importance is in terms of 1, 2, 3, 4, 5, and so on, based on how significant they are in relation to each other. An average rank will be given if two or more attributes are thought to be equally important.

For example, let there are three selection attributes—*X*, *Y*, and Z— and the ranks of 1, 2, and 3 are assigned to them. Matrix *M1* shows the rank relations.

$$M1= \begin{array}{c} \\ X \\ Y \\ Z \end{array} \begin{array}{c} \begin{array}{ccc} X & Y & Z \end{array} \\ \begin{bmatrix} 1 & 2 & 3 \\ 1/2 & 1 & 3/2 \\ 1/3 & 2/3 & 1 \end{bmatrix} \end{array}$$

It may be noted that in matrix M_1, the diagonal elements are 1 (i.e., r_{xx} =1, r_{yy} =1, r_{zz} =1, etc.) and the elements below the diagonal are the reciprocals of the rank relations of the selection attributes given above the diagonal (i.e., r_{yx} =1/r_{xy}, r_{zy} =1/r_{yz}, and r_{zx} =1/ r_{xz}).

The arithmetic means of each row of the *M1* matrix are calculated and these are 2 (i.e., (1+2+3)/3), 1 (i.e., (1/2+1+3/2)/3), and 0.66666 (i.e., (1/3+2/3+1)/3) respectively. The grand summation of the arithmetic means of the rows is equal to 3.66666 (i.e., 2 + 1 + 0.66666). Now dividing each the arithmetic mean of each row with the grand sum of 3.66666 gives the *M2* matrix, which corresponds to the weights of the five selection attributes considered.

$$M2 = \begin{bmatrix} 0.545454 \\ 0.272727 \\ 0.181818 \end{bmatrix}$$

If the consistency check is performed, like in Analytic Hierarchy Process (AHP) and Best-Worst Method (BWM) approaches, to check for consistency of rank relations provided in matrix *M*1, the matrix *M*3 is computed as *M*1* *M*2.

$$M3 = M1*M2 = \begin{bmatrix} 1.63636 \\ 0.81818 \\ 0.54545 \end{bmatrix}$$

Now *M4* matrix is computed as *M3*/*M2*. Each element of *M3* is divided by the corresponding element of *M2*. For example, 1.63636/0.545454=3; 0.81818/0.272727=3; 0.545454/0.181818=3.

$$M4 = M3/M2 = \begin{bmatrix} 3.00000 \\ 3.00000 \\ 3.00000 \end{bmatrix}$$

Now the maximum Eigen value (λmax) is computed.

λmax = Average of *M4* = (3+3+3)/3 = 3.

Consistency Index (CI) = ($\lambda max - m$)/(m-1)=(3-3)/(3-1) = 0; m= no. of attributes=size of *M1* matrix=3.

The CI value of 0 indicates that the rank relations provided in *M1* matrix are *absolutely consistent* and there is no error present in the judgements of rank relations. As a result, weights of 0.545454, 0.272727, and 0.181818 can be assigned to the attributes *X*, *Y*, and *Z* having ranks 1, 2, and 3 respectively. By expanding this method to any number of attributes and giving each one a rank, the attributes' weights may be found. It may be stated here that techniques such as AHP and BWM hardly provide absolute consistency in the assessments of relative importance. Thus, the proposed method is more reliable and dependable.

Step 3: For every alternative of the given refrigerant selection problem, obtain the performance data corresponding to the pertinent selection attributes. The performances may be in qualitative or quantitative terms. Transform the qualitative attribute data (expressed in descriptive language) into quantitative data by applying a straightforward scale and avoiding the use of fuzzy logic.

Rao (2024a) proved that there is no need of using fuzzy scales and simple ordinary scales will serve the same purpose. Different membership functions available in fuzzy logic (such as triangular, trapezoidal, S-shape, Beta shape, Gaussian shape, etc.) may lead to different values for the same linguistic or qualitative description of the attribute!! The use of fuzzy approaches such as orthogonal, pythagorean, etc. do not guarantee the accuracy of decision-making. Fuzzification and the subsequent defuzzification may take away the elegance of the available information about the attributes data. There is no strong evidence yet that the fuzzy logic scales provide a better decision-making advantage compared to the simple scales (when applied to the same MADM problems). Simple ordinary scales can simply replace the fuzzy scales provided by different researchers to deal with linguistic or qualitative attributes. Table 1, for example, shows the transformation of a qualitative or linguistic attribute into a quantitative attribute on 11-point scale. The linguistic terms given in Table 1 are suggestive and the user may use similar terms depending upon his application requirements. For more details, one may refer to Rao (2024a, b, c), Rao (2013), and Rao and Lakshmi (2024).

doi.org/10.32388/94AKJ7.2

Linguistic expression	Fuzzy scale value for a beneficial attribute using triangular membership function (Rao, 2013)	Simple scale value for a beneficial attribute without using any fuzzy membership function	Fuzzy scale value for a non-beneficial attribute using triangular membership function	Simple scale value for a non-beneficial attribute without using any fuzzy membership function
Exceptionally low	0.0450	0.0	0.9545	1.0
Extremely low	0.1364	0.1	0.8636	0.9
Very low	0.2273	0.2	0.7727	0.8
Low	0.3182	0.3	0.6818	0.7
Below average	0.4091	0.4	0.5909	0.6
Average	0.5	0.5	0.5	0.5
Above average	0.5909	0.6	0.4091	0.4
High	0.6818	0.7	0.3182	0.3
Very high	0.7727	0.8	0.2273	0.2
Extremely high	0.8636	0.9	0.1364	0.1
Exceptionally high	0.9545	1.0	0.0450	0

Table 1. Transformation of a qualitative attribute into a quantitative attribute using 11-point scale.

Step 4: Normalize the data for a selection attribute by comparing it to the attribute's "best" value for various alternatives. To obtain the normalized data, repeat this normalization process for each attribute. When referring to a beneficial attribute, the term "best" denotes the highest value that is available, and when referring to a non-beneficial attribute, the lowest value that is available. Normalization is required for the performance measurements of alternatives. For a beneficial attribute, the normalized value $(x_{ji})_{norm}$ is $x_{ji}/x_{i\text{-}best}$; and for a non-beneficial attribute, it is $x_{i\text{-}best}/x_{ji}$. The i-th attribute's best value is represented by $x_{i\text{-}best}$. The standing positions of the alternatives in relation to the "best" values of the attributes are clearly displayed by this kind of normalization of the data with reference to the "best" values.

Step 5: Overall score of an alternative is $\sum w_i*(x_{ji})_{norm}$ and it is the result of multiplying the selection attributes' weights with the corresponding normalized data of the attributes for the alternatives. Arrange the alternatives in decreasing order, based on overall scores. The alternative that receives the highest overall score is considered best for the particular refrigerant selection problem investigated.

It may be understood that the proposed BHARAT-II method offers a general decision-making methodology and is not meant for refrigerant selection only. In this paper, the proposed BHARAT-II method is applied to the case studies of refrigerant selection in air conditioning applications mainly to demonstrate the applicability and validity of the proposed method.

3. Applications of proposed decision-making method to the case studies of refrigerant selection

3.1. Case study 1: Choosing the best refrigerant for a split air conditioner system

Prabakaran et al. (2022) considered 15 refrigerants with a view to replace R22 in split AC units with a 1.5 TR capacity. The thermodynamic analysis of each refrigerant's performance was conducted, and the findings were compared with R22 while taking into consideration the discharge temperature, power consumption, coefficient of performance (COP), and total equivalent warming impact (TEWI) index and the lifetime cost. The thermodynamic properties of the refrigerants, environmental and economic conditions considered by Prabakaran et al. (2022) are given in Table 2.

Refrigerant	Composition (wt%)	T ↑	Cpr ↓	Spr ↓	LD ↓	VD ↑	LH ↑	TC ↑	VL ↓	P ↓	ODP ↓	GWP ↓	Toxicity and Flammability ↓
R22	-	178.3	51.8	5.84	1264	24.79	200.9	92.49	204.5	24.3	0.05	1700	A1 (1)
R410A (R32/R125)	49.5/50.5	71.34	49.01	9.36	1150	35.86	215.2	100.4	151.9	38.4	0	2088	A1 (1)
R32	-	78.1	57.82	9.51	1038	25.89	307.3	141.3	142.3	39.3	0	650	A2 (0.5)
R290	-	96.74	42.5	5.51	621.8	11.9	366.7	103.4	119	21.2	2	1	A3 (0.3)
R161	-	102.1	50.46	5.13	738.9	12.08	368.1	123.5	147.6	21.7	0	12	A3 (0.3)
R1270	-	91.06	45.5	6.76	538.6	14.2	369.8	93	115.2	25.2	2	1	A3 (0.3)
R1123	-	58.58	45.26	12.5	1104	56.67	164.8	81.89	144.6	45.34	0	3	A2L (0.8)
R32/R1123	60/40	67.4	54.5	12.1	1042	41.98	224.9	113.7	132.8	46.5	0	407	A2L (0.8)
R1234yf	-	95	34	3.73	1160	20.7	160	74	196	16.4	0	4	A2L (0.8)
R454B (R32/R1234yf)	68.9/31.1	78.1	52.66	8.88	1064	27.43	267.2	118.2	144.5	36.2	0	467	A2L (0.8)
R452B (R32/R125/R1234yf)	67/7/26	77.09	52.2	8.96	1074	28.37	260.8	116.1	145	36.6	0	675	A2L (0.8)
R454C (R32/R1234yf)	21.5/78.5	85.67	43.18	6.8	118.8	26.75	210.5	83.98	164.5	26.8	0	146	A2L (0.8)
R444B (R32/R152a/R1234ze (E))	41.5/10/48.5	95.62	53.84	6.95	1114	21.76	265.9	111	174.4	28	0	295	A2L (0.8)
R433A (R290/R1270)	70/30	94.41	43.54	5.98	526	12.86	366.7	105.9	117.1	22.6	0	3	A3 (0.3)
RM30 (R152a/R1270/RE170)	25/71/4	91.16	45.32	6.54	601	14.99	346.3	111.8	121.6	24.9	0	37	A3 (0.3)

Table 2. Twelve properties and characteristics (i.e., attributes) of 15 refrigerants.

T: Critical Temperature (^{0}C); Cpr: Critical Pressure (bar); Spr: Saturated pressure (bar); LD: Liquid density (kg/m^3); VD: Vapor density (kg/m^3); LH: Latent heat of vaporization (kJ/kgK); TC: Thermal conductivity of liquid (mW/mK); VL: Viscosity of liquid (μPa.s); P: Pressure at 60 °C (bar); ODP: Ozone Depletion Potential; GWP: Global Warming Potential (100 yrs); TF: Toxicity and flammability.
A1: Not flammable; A2L: Very low flammable; A2: Medium flammable; A3: Highly flammable.

Now to select a best alternative refrigerant out of the 15 refrigerants, the steps of the proposed decision-making method are carried out as described below.

Step 1: Table 2 shows the refrigerant selection attributes and the alternative refrigerants. These are same as those considered by Prabakaran et al. (2022). The attributes T, VD, LH, and TC are the beneficial attributes and are indicated by upward arrows. The other attributes are the non-beneficial attributes and are indicated by downward arrows. The attribute "Toxicity and flammability" is a non-beneficial attribute (and lower values are desired) described qualitatively and the corresponding quantitative values are assigned using Table 1. The numbers in parenthesis in Table 2 represent the appropriate quantitative values that are assigned using a simple 11-point scale.

Step 2: To determine the weights of the selection attributes, ranks are assigned. The environmental attributes of ODP, GWP, and Toxicity and flammability are considered equally important. Hence, an average rank of 2 (i.e., (1+2+3)/3) is assigned to OWP, GWP, and Toxicity and flammability. The thermodynamic properties are all considered equally important and hence an average rank of 8 (i.e., (4+5+6+7+8+9+10+11+12)/9) is assigned to the thermodynamic properties. It may be mentioned here that in actual practice, the decision-maker can assign these ranks in terms of 1, 2, 3, 4, 5, etc. as per his/her preferences. The ranks assigned here are only for demonstration.

The rank relationships and weights of the 12 selection attributes are shown in Table 3. The calculated weights of the attributes are shown in the last column of Table 3. The CI value for the rank relations matrix containing 12 selection attributes is 0. Thus, there exists absolute consistency in the judgments of rank relations.

doi.org/10.32388/94AKJ7.2

Refrigerant selection attributes	Refrigerant selection attributes												Means of rows	Weights of attributes
	T	Cpr	Spr	LD	VD	LH	TC	VL	P	ODP	GWP	TF		
T	1*	1	1	1	1	1	1	1	1	1/4**	1/4	1/4	0.8125	0.047619
Cpr	1	1	1	1	1	1	1	1	1	1/4	1/4	1/4	0.8125	0.047619
Spr	1	1	1	1	1	1	1	1	1	1/4	1/4	1/4	0.8125	0.047619
LD	1	1	1	1	1	1	1	1	1	1/4	1/4	1/4	0.8125	0.047619
VD	1	1	1	1	1	1	1	1	1	1/4	1/4	1/4	0.8125	0.047619
LH	1	1	1	1	1	1	1	1	1	1/4	1/4	1/4	0.8125	0.047619
TC	1	1	1	1	1	1	1	1	1	1/4	1/4	1/4	0.8125	0.047619
VL	1	1	1	1	1	1	1	1	1	1/4	1/4	1/4	0.8125	0.047619
P	1	1	1	1	1	1	1	1	1	1/4	1/4	1/4	0.8125	0.047619
ODP	4#	4	4	4	4	4	4	4	4	1	1	1	3.25	0.190476
GWP	4	4	4	4	4	4	4	4	4	1	1	1	3.25	0.190476
TF	4	4	4	4	4	4	4	4	4	1	1	1	3.25	0.190476
Total =													17.0625	1.000000

Table 3. Rank relationships of the 12 refrigerant selection attributes of case study 1.

**1 = (2/2); **1/4 = (2/8); #4 = (8/2). Remember that the average rank assigned to ODP, GWP, and Toxicity and flammability is 2 and the average rank assigned to the other attributes is 8.*

Step 3: The linguistic expressions of the attribute “Toxicity and flammability (TF)” transformed to quantitative values using Table 1 without the need of using fuzzy logic. These values are shown in Table 2 in parentheses. After assigning like this, the assigned values TF can be considered beneficial for the sake of normalization.

Step 4: The data is normalized based on the "best" refrigerant for each attribute. Table 4 shows the normalized values. For example, the normalized value of 0.400112 for R410A (R32/R125) corresponding to the attribute T is obtained by (71.34/178.3); the normalized value of 0.656371 for R22 corresponding to Cpr is obtained by (34/51.8). Similarly, the other data is normalized and given in Table 4.

doi.org/10.32388/94AKJ7.2

Refrigerant	Refrigerant selection attributes											
	T	Cpr	Spr	LD	VD	LH	TC	VL	P	ODP	GWP	TF
R22	1	0.656371	0.638699	0.093965	0.437445	0.543267	0.654518	0.563389	0.674897	0	0.000588	1
R410A (R32/R125)	0.400112	0.693736	0.398504	0.10334	0.632786	0.581801	0.710282	0.758791	0.427083	1	0.000479	1
R32	0.438026	0.588032	0.392219	0.114484	0.456855	0.831017	1	0.809541	0.417303	1	0.001538	0.5
R290	0.542569	0.8	0.676951	0.191074	0.209988	0.991698	0.731937	0.968319	0.773585	0	1	0.3
R161	0.57263	0.673801	0.727096	0.16078	0.213164	0.995484	0.874248	0.78085	0.75576	1	0.083333	0.3
R1270	0.510712	0.747253	0.551775	0.220572	0.250573	1	0.658128	1	0.650794	0	1	0.3
R1123	0.328547	0.751215	0.2984	0.10757	1	0.445673	0.579506	0.796998	0.361712	1	0.333333	0.8
R32/R1123	0.378015	0.623853	0.308264	0.113979	0.74078	0.608167	0.804685	0.867826	0.352688	1	0.002457	0.8
R1234yf	0.53281	1	1	0.102378	0.365273	0.43272	0.523671	0.587908	1	1	0.25	0.8
R454B (R32/R1234yf)	0.438026	0.645651	0.420045	0.111707	0.48403	0.722472	0.8366	0.797439	0.453039	1	0.002141	0.8
R452B (R32/R125/R1234yf)	0.432361	0.651341	0.416295	0.110635	0.500618	0.705354	0.821881	0.794799	0.448087	1	0.001481	0.8
R454C (R32/R1234yf)	0.480482	0.787402	0.548529	1	0.472031	0.569173	0.594296	0.700614	0.61194	1	0.006849	0.8
R444B (R32/R152a/R1234ze (E))	0.536287	0.631501	0.536691	0.106691	0.383977	0.718956	0.785153	0.660685	0.585714	1	0.00339	0.8
R433A (R290/R1270)	0.529501	0.780891	0.623746	0.225847	0.226928	0.991617	0.749204	0.984367	0.725664	1	0.333333	0.3
RM30 (R152a/R1270/RE170)	0.511273	0.750221	0.570336	0.197667	0.264514	0.936533	0.791168	0.947693	0.658635	1	0.027027	0.3

Table 4. Normalized values for case study 1.

Step 5: Overall scores of alternative refrigerants are calculated by multiplying the selection attributes' weights with the corresponding normalized data of the attributes for the alternative refrigerants. For example, the overall score of the refrigerant "R22" is computed as,

Overall score (R22) = 0.047619*1 + 0.047619*0.656371 + 0.047619*0.638699 + 0.047619*0.093965 + 0.047619*0.437445 + 0.047619*0.543267 + 0.047619*0.654518+ 0.047619*0.563389+ 0.047619*0.674897 + 0.190476*0 + 0.190476*0.000588 + 0.190476*1 = 0.441185.

Table 5 shows the refrigerants and the overall scores, and the ranks of the refrigerants.

doi.org/10.32388/94AKJ7.2

Refrigerants	Overall scores	Ranks
R22	0.441185	15
R410A (R32/R125)	0.605159	4
R32	0.526363	12
R290	0.52791	11
R161	0.537483	10
R1270	0.5138	14
R1123	0.628712	2
R32/R1123	0.571813	9
R1234yf	0.654512	1
R454B (R32/R1234yf)	0.577027	7
R452B (R32/R125/R1234yf)	0.575585	8
R454C (R32/R1234yf)	0.61866	3
R444B (R32/R152a/R1234ze (E))	0.57901	6
R433A (R290/R1270)	0.589099	5
RM30 (R152a/R1270/RE170)	0.520768	13

Table 5. Overall scores and the ranks of the refrigerants.

With the highest overall score, the refrigerant "R1234yf" can be considered as the best choice for the given application for the considered weights of the selection attributes. The second choice is R1123 and the last choice is R22. It may be noted that Prabakaran et al. (2022) used the 12 selection attributes and calculated certain factors such as the discharge temperature, power consumption, coefficient of performance (COP), and total equivalent warming impact (TEWI) index and the lifetime cost. In fact, the thermodynamic properties, environmental, and safety conditions mentioned in Table 2 can also be used directly to decide about the selection of best refrigerant.

A point to be noted is that Prabakaran et al. (2022) used entropy method (which assigns objective weights to the attributes based on their numerical values but without considering the decision-maker's preferences) to get the weights of the attributes. They did not mention the values of those attributes' weights in their paper. Using those unexplained entropy weights, Prabakaran et al. (2022) applied an MADM method known as "Evaluation based on distance from the average solution (EDAS)" and proposed R290 as the first choice, R433A as the second choice, R22 as the third choice, and R1123 as the last choice.

In a communication with Prabakaran et al. (2022), the first author of this paper received information that the objective weights considered by Prabakaran et al. (2022) for T, Cpr, TC, VL, TF, etc. were 0.1715, 0.03713, 0.06274, 0.07170.4225, etc. This means that the objective weights obtained by the entropy method for the selection attributes were completely different from the weights used in the present work and hence the final ranks differed. A highly surprising thing is that the entropy method used by Prabakaran et al. (2022) had given a bigger weight of 0.4225 (i.e., 42.25%)! to the attribute of "Toxicity and flammability (TF)" and weight of 0.1715 (i.e., 17.15%) was assigned to the attribute "Critical temperature (T)". The weights assigned to the very important attributes of ODP and GWP were not mentioned.

However, it is to be noted that the objective weights are based on the given values of the attributes and the decision-maker plays no role. For example, let us consider that a decision-maker, based on his knowledge and experience, gives a weight of 0.20 to an attribute. However, when objective weights calculation is done by entropy method, depending upon the numerical values of that attribute and the normalization procedure followed in entropy method, the entropy method may compute the weight as 0.42, which is completely different from the weight of 0.20 obtained based on the knowledge and experience of the decision-maker. A similar situation may occur in the case of other attributes. The opinions of the decision-makers who deal with the practical importance of the attributes in each decision-making situation are then not taken into consideration, which could make the evaluation and rankings of the alternatives using such objective attributes' weights worthless. There are a lot of these pointless exercises in literature! Why then do

MADM problems require objective weights? If an individual or a group of individuals cannot articulate their preferences on the importance of particular attributes, how can they be regarded as decision-makers? Lately, a few studies have begun use composite weights, which combine the objective and subjective weights. This could be just another pointless exercise done only to have anything published. Are these objective weights or composite weights employed at all in actual decision-making scenarios? Of course, the response is no. These kinds of exercises are typically conducted for academic purposes (Rao, 2024a, 2024b).

An interesting point to mention here is that the proposed method has a provision of directly assigning the weights to the attributes as decided by the decision-maker based on his knowledge and experience. For example, let us assume the decision-maker considers ODP, GDP, and TF as equally important and directly assigns a weight of 0.20 to each of them. Considering all other thermodynamic properties as equally important, he may directly assign a weight of 0.4/9 = 0.044444 to each of the nine attributes. Using these weights, and the normalized data of the attributes for 15 alternative refrigerants given in Table 4, the overall scores are calculated and given in Table 6.

doi.org/10.32388/94AKJ7.2

Refrigerants	Overall scores	Ranks
R22	0.434009	15
R410A (R32/R125)	0.609271	4
R32	0.52464	11
R290	0.521605	12
R161	0.532391	10
R1270	0.508436	14
R1123	0.634205	2
R32/R1123	0.573747	9
R1234yf	0.656434	1
R454B (R32/R1234yf)	0.578606	7
R452B (R32/R125/R1234yf)	0.577246	8
R454C (R32/R1234yf)	0.617568	3
R444B (R32/R152a/R1234ze (E))	0.580485	6
R433A (R290/R1270)	0.586123	5
RM30 (R152a/R1270/RE170)	0.51554	13

Table 6. Overall scores and the ranks of the refrigerants (if weights are assigned directly)

With the highest overall score, the refrigerant "R1234yf" can be considered as the best choice for the given application for the considered weights of the selection attributes. The second choice is R1123 and the last choice is R22. This ranking is matching well with the ranks shown in Table 5. Thus, the proposed method has a provision of directly assigning the weights to the attributes as decided by the decision-maker based on his knowledge and experience. Alternative procedure of assigning weights to the attributes is preparing the rank relations as explained in Table 3.

It may be noted that the proposed decision-making method is involved in simple normalization procedure and the calculation of overall scores of alternative refrigerants compared to the computationally intensive EDAS and entropy methods. The ranks assignment procedure and the subsequent determinations of the weights of the selection attributes by the decision-maker are more logical compared to the entropy weights used by Prabakaran et al. (2022). The decision-makers preferences are taken into account in the proposed method. The proposed method makes it easy to convert qualitative attributes into quantitative, and does not require the use of fuzzy scale.

3.2. Case study 2: Choosing the best alternative refrigerant for the automobile air conditioning system

Poongavanam et al. (2022) used three distinct MADM methods to select the best refrigerant for n automobile air conditioning system. The MADM methods used were: Evaluation based on distance from the average solution (EDAS), Technique for order preference by similarity to ideal solution (TOPSIS) method, and multi-objective optimization based on ratio analysis (MOORA) method. The selection attributes included the thermodynamic properties of the refrigerants, environmental friendliness, and economic conditions. The 13 selection attributes included: T, Cpr, Spr, LD, VD, LH, TC, VL, P, ODF, GWP, TF, and Cost per kg (C). The attributes except ODP, GWP, and TF were described already on a scale by Poongavanam et al. (2022). For fair comparison, the same scaled values are taken in the present work. Of the 13 selection attributes, the attributes T, VD, LH, and TC are the beneficial attributes and the remaining are the non-beneficial attributes (i.e., lower values are desirable).

Now to select a best refrigerant out of the 14 available refrigerants, the steps of the proposed decision-making method are carried out as described below.

<u>Step 1</u>: Table 7 shows the refrigerant selection attributes and the alternative refrigerants. These are same as those considered by Poongavanam et al. (2022).

Refrigerants	Refrigerant selection attributes												
	T ↑	Cpr ↓	Spr ↓	LD ↓	VD ↑	LH ↑	TC ↑	VL ↓	P ↓	ODP ↓	GWP ↓	TF ↓	C ↓
R134a	102	41	3.49	1278.1	17.1	194.7	0.089	250	16.8	1	4	1	5
R152a	113.4	45.1	3.14	947.7	9.89	301.9	0.106	206	15	1	1	2	5.5
R1234yf	95	34	3.73	1160.4	20.7	160.02	0.074	196	16.4	1	1	1	12.33
R1234ze (E)	109.4	36.3	2.59	1111.5	40.6	154.8	0.078	269	12.7	1	1	1	53
R1233zd (E)	166.6	36.2	0.59	1319.8	35.6	188.52	0.081	470	38.7	1	1	1	39.5
R290	96.74	42.5	5.51	521.75	11.9	367.73	0.103	119	21.2	2	1	4	5.98
R600a	134.6	36.3	1.87	574.8	5.01	349.56	0.097	187	8.69	2	1	4	10
R744	30.98	73.8	39.7	896.03	114	214.98	0.104	90.8		1	1	1	10.91
R1270	91.06	45.5	6.76	538.6	14.2	369.8	0.093	115	25.2	2	1	4	4.5
R744 + R290	57	67.9	29.9	644.9	78.3	217.4	0.083	87.7	8.69	2	1	4	9
R430A	106.9	40.8	3.5	802.1	10.7	295.2	0.984	180	15.7	2	1	4	7
R436A	115.9	42.7	3.85	548.01	8.66	365.5	0.1	146	15.1	2	1	4	8
R444A	101.2	42.3	4.47	1199.1	28.5	180.5	0.9	225	19.8	1	1	1	50
R445A	104.7	44.9	4.67	1190	29.4	190.4	0.95	220	19.4	1	1	1	46

Table 7. Data of the 13 attributes and 14 alternative refrigerants of case study 2.

Step 2: To determine the weights of the 13 selection attributes, ranks are assigned. The environmental and safety attributes of ODP, GWP, and TF are considered equally important and hence an average rank of 2 (i.e., (1+2+3)/3) is given to each of them. The attribute Cost per kg (C) is given rank 4. All thermodynamic properties are considered equally important and hence an average rank of 9 (i.e., (5+6+7+8+9+10+11+12+13)/9) is assigned to each of the thermodynamic properties. The rank relationships and weights of the 13 attributes are shown in Table 8. It may be mentioned here that in actual practice, the decision-maker can assign these ranks in terms of 1, 2, 3, 4, etc. as per his preferences. The ranks assigned here are only for demonstration.

Refrigerant selection attributes	Refrigerant selection attributes													Means of rows	Weights of attributes
	T	Cpr	Spr	LD	VD	LH	TC	VL	P	ODP	GWP	TF	C		
T	1*	1	1	1	1	1	1	1	1	2/9	2/9	2/9	4/9	0.777778	0.040404
Cpr	1	1	1	1	1	1	1	1	1	2/9	2/9	2/9	4/9	0.777778	0.040404
Spr	1	1	1	1	1	1	1	1	1	2/9	2/9	2/9	4/9	0.777778	0.040404
LD	1	1	1	1	1	1	1	1	1	2/9	2/9	2/9	4/9	0.777778	0.040404
VD	1	1	1	1	1	1	1	1	1	2/9	2/9	2/9	4/9	0.777778	0.040404
LH	1	1	1	1	1	1	1	1	1	2/9	2/9	2/9	4/9	0.777778	0.040404
TC	1	1	1	1	1	1	1	1	1	2/9	2/9	2/9	4/9	0.777778	0.040404
VL	1	1	1	1	1	1	1	1	1	2/9	2/9	2/9	4/9	0.777778	0.040404
P	1	1	1	1	1	1	1	1	1	2/9	2/9	2/9	4/9	0.777778	0.040404
ODP	9/2	9/2	9/2	9/2	9/2	9/2	9/2	9/2	9/2	1	1	1	2	3.5	0.181818
GWP	9/2	9/2	9/2	9/2	9/2	9/2	9/2	9/2	9/2	1	1	1	2	3.5	0.181818
TF	9/2	9/2	9/2	9/2	9/2	9/2	9/2	9/2	9/2	1	1	1	2	3.5	0.181818
C	9/4	9/4	9/4	9/4	9/4	9/4	9/4	9/4	9/4	1/2	1/2	1/2	1	1.75	0.090909
Total =														19.25	1.000000

Table 8. Rank relationships of the 13 refrigerant selection attributes of case study 2.

**1 = (2/2); Remember that the average rank assigned to ODP, GWP, and Toxicity and flammability is 2 and the average rank assigned to the other attributes is 9.*

The calculated weights of the attributes are shown in the last column of Table 8. The CI value for the rank relations matrix containing 13 selection attributes is 0. Thus, there exists absolute consistency in the judgments of rank relations.

Step 3: The attributes ODP, GWP, and TF are already assigned on a scale by Poongavanam et al. (2022) and hence the same scaled values are considered in this present work for normalization.

Step 4: The data is normalized based on the "best" refrigerant for each attribute. Table 9 shows the normalized values. It is observed from the calculations of Poongavanam et al. (2022) that they had adapted a value of 8.69 bar for the critical pressure at 60^0C for the refrigerant R744. Hence the same value is considered for normalization.

doi.org/10.32388/94AKJ7.2

Refrigerants	Refrigerant selection attributes												
	T	Cpr	Spr	LD	VD	LH	TC	VL	P	ODP	GWP	TF	C
R134a	0.612245	0.829268	0.169054	0.408223	0.15	0.526501	0.090447	0.3508	0.517262	1	0.25	1	0.9
R152a	0.680672	0.75388	0.187898	0.550543	0.086754	0.816387	0.107724	0.425728	0.579333	1	1	0.5	0.818182
R1234yf	0.570228	1	0.158177	0.449629	0.181579	0.43272	0.075203	0.447449	0.529878	1	1	1	0.364964
R1234ze (E)	0.656663	0.936639	0.227799	0.469411	0.35614	0.418605	0.079268	0.326022	0.684252	1	1	1	0.084906
R1233zd (E)	1	0.939227	1	0.395325	0.312281	0.509789	0.082317	0.186596	0.224548	1	1	1	0.113924
R290	0.580672	0.8	0.107078	1	0.104386	0.994402	0.104675	0.736975	0.409906	0.5	1	0.25	0.752508
R600a	0.807923	0.936639	0.315508	0.907707	0.043947	0.945268	0.098577	0.468984	1	0.5	1	0.25	0.45
R744	0.185954	0.460705	0.014861	0.582291	1	0.581341	0.105691	0.965859	1	1	1	1	0.412466
R1270	0.546579	0.747253	0.087278	0.968715	0.124561	1	0.094512	0.762609	0.344841	0.5	1	0.25	1
R744 + R290	0.342137	0.500736	0.019732	0.80904	0.686842	0.587885	0.08435	1	1	0.5	1	0.25	0.5
R430A	0.641657	0.833333	0.168571	0.65048	0.09386	0.798269	1	0.487222	0.553503	0.5	1	0.25	0.642857
R436A	0.695678	0.796253	0.153247	0.952081	0.075965	0.988372	0.101626	0.600685	0.575497	0.5	1	0.25	0.5625
R444A	0.607443	0.803783	0.131991	0.435118	0.25	0.488102	0.914634	0.389778	0.438889	1	1	1	0.09
R445A	0.628451	0.757238	0.126338	0.438445	0.257895	0.514873	0.965447	0.398636	0.447938	1	1	1	0.097826

Table 9. Normalized data of the 13 attributes and 14 alternative refrigerants of case study 2.

Step 5: Overall scores of alternative refrigerants are calculated by multiplying the selection attributes' weights with the corresponding normalized data of the attributes for the alternative refrigerants. The overall scores of the refrigerants and their overall ranks are given in Table 10.

doi.org/10.32388/94AKJ7.2

Refrigerants	Overall scores	Ranks
R134a	0.638537	8
R152a	0.698174	7
R1234yf	0.73398	4
R1234ze (E)	0.721043	6
R1233zd (E)	0.743693	2
R290	0.58207	12
R600a	0.582305	11
R744	0.780797	1
R1270	0.598034	9
R744 + R290	0.566897	14
R430A	0.58781	10
R436A	0.568889	13
R444A	0.733827	5
R445A	0.73759	3

Table 10. Overall scores and the ranks of the refrigerants of case study 2.

With the highest overall score, the refrigerant "R744" refrigerant can be considered as the best choice for the given application. The refrigerant R1233zd (E) is the second choice and R744 + R290 is the last choice.

It may be noted that Poongavanam et al. (2022) used EDAS, TOPSIS, and MOORA methods considering the 13 selection attributes and proposed R430A as the first choice, R445A as the second choice, and R444A as the third choice. The ranks of the all other refrigerants differed significantly within these three methods used by Poongavanam et al. (2022)! Furthermore, a point to be noted is that Poongavanam et al. (2022) used entropy method (which assigns objective weights to the attributes based on their numerical values but without considering the decision-maker's preferences) to get the weights of the attributes. They did not mention the values of those attributes' weights in their paper. Using those unexplained entropy weights, Poongavanam et al. (2022) applied the EDAS, TOPSIS, and MOORA methods. This means that the objective weights obtained by the entropy method for the selection attributes were completely different from the weights used in the present work and hence the final ranks differed. However, it is already mentioned in case study 1 that the objective weights are based on the given values of the attributes and the decision-maker plays no role. The opinions of the decision-makers who deal with the practical importance of the attributes in each decision-making situation are not taken into consideration, which could make the evaluation and rankings of the alternatives using such objective attributes' weights meaningless.

As mentioned already the proposed method has a provision of directly assigning the weights to the attributes as decided by the decision-maker based on his knowledge and experience. For example, let us assume the decision-maker considers ODP, GDP, and TF as equally important and directly assigns a weight of 0.20 to each of them and a weight of 0.10 to C. Considering all other thermodynamic properties as equally important, he may directly assign a weight of 0.3/9 = 0.033333 to each of the nine attributes. Using these weights, and the normalized data of the attributes for 14 alternative refrigerants given in Table 9, the overall scores are calculated and given in Table 11.

doi.org/10.32388/94AKJ7.2

Refrigerants	Overall scores	Ranks
R134a	0.661792	8
R152a	0.721447	7
R1234yf	0.764657	3
R1234ze (E)	0.746982	6
R1233zd (E)	0.766394	2
R290	0.586519	11
R600a	0.57915	12
R744	0.804468	1
R1270	0.605877	9
R744 + R290	0.567689	14
R430A	0.588514	10
R436A	0.570895	13
R444A	0.757656	5
R445A	0.760957	4

Table 11. Overall scores and the ranks of the refrigerants of case study 2 (if weights are assigned directly).

With the highest overall score, the refrigerant "R744" can be considered as the best choice for the given application for the considered weights of the selection attributes. The second choice is refrigerant R1233zd (E) is the second choice and R744 + R290 is the last choice. This ranking is closer to the ranks shown in Table 10. Thus, the proposed method has a provision of directly assigning the weights to the attributes as decided by the decision-maker based on his knowledge and experience. Alternative procedure of assigning weights to the attributes is preparing the rank relations as explained in Table 8.

It may be noted once again that the proposed decision-making method is involved in simple normalization procedure and the calculation of overall scores of alternative refrigerants compared to the computationally intensive EDAS, TOPSIS, and MOORA methods and entropy methods. The ranks assignment procedure and the subsequent determinations of the weights of the selection attributes by the decision-maker are more logical compared to the entropy weights used by Poongavanam et al. (2022).

Here one may get a doubt about the sensitivity of the weights obtained by the proposed BHARAT-II method. Sensitivity analysis means, seeing the effect of changing the weights of the attributes on the decision-making process. However, it must be mentioned here that once a decision-maker has assigned ranks such as 1, 2, 3, etc. to the attributes means that it is as per his/her understanding of the given decision-making problem and is based on his/her preferences of importance of those attributes. Then he/she can proceed further with the steps of the proposed methodology. Then where is the need to change the weights of the attributes (i.e., assigning different ranks to the attributes)? How can he/she can be called decision-maker if he/she himself/herself does not have clear idea about the importance of the attributes? Only for academic purpose, one may try changing the ranks and thereby the weights of the attributes and see upto which range the weights are stable. But all this sensitivity analysis may not be really useful in practical situations and may be useful for academic purpose. In case of group decision-making, the average opinion about each attribute can be considered and the proposed method can be applied, as explained in Rao (2024a).

An important observation is that the researchers used the properties and characteristics of the refrigerants for selection of a best refrigerant from amongst the available refrigerants. Using the available data related to the properties and characteristics a large number of refrigerants, the researchers used MADM methods and conducted simulation studies to choose a best refrigerant for the given application. After choosing a particular refrigerant, the researchers had then suggested that particular refrigerant for use in the given application. However, *real experimentation* was less conducted by the researchers on the alternative refrigerants to decide the selection of right refrigerant. It was because of the difficulty of experimenting on a large number of refrigerants which is a costly and time-consuming activity. Only limited number of research works are available on the real experimentation conducted on the refrigerants for the purpose of selecting a best refrigerant out of the available ones. However, the number of refrigerants experimented in such works is very less, because of the difficulty of experimenting on a large number of refrigerants.

4. Conclusions

Selection of a suitable refrigerant for a given application is not an easy task. A number of selection attributes such as the thermodynamic properties of the refrigerants, environmental and safety attributes such as ODP, GWP, flammability, toxicity, economic conditions such as cost of the refrigerant have to considered together. The researchers have started using different MADM methods such as EDAS, TOPSIS, MOORA, VIKOR, GRA, SAW, etc. in conjunction with the weights of the attributes obtained mostly by the entropy method. However, the entropy method does not take into account the actual decision-makers preferences or choices in deciding the weights of the attributes. Different normalization procedures adopted in entropy method will lead to different weights of the attributes. All this leads to incorrect decisions of refrigerant selection.

A simple and effective decision-making method, named as "Best Holistic Adaptable Ranking of Attributes Technique (BHARAT)-II, is proposed in this paper for best refrigerant selection for a given application. Two case studies of refrigerant selection are presented to illustrate the potential of the proposed methodology. The first case study addressed the issue of choosing the best refrigerant for residential split air conditioning systems by considering 15 different refrigerants and 12 selection attributes; the second case study addressed the problem of selecting the best refrigerant for automobile air conditioning systems by considering 14 different refrigerants and 13 selection attributes. It may be understood by the readers that the proposed method considered the same selection attributes and the alternative refrigerants of the two respective case studies for fair comparison. If more attributes and alternatives are to be considered by the decision-maker, he/she can include the related data and then the proposed method can be applied without any difficulty.

A novel feature of the proposed method is that, it simply ranks all of the attributes according to their priority as per the understanding of the decision-maker. A relative importance matrix is then created using these ranks to further establish the weights. This idea has the advantage of ensuring consistency while prioritizing one attribute over another. The consistency index is always 0 (i.e., fully consistent). In AHP or BWM, this is not feasible, particularly for the decision-making problems containing a large number of attributes.

The second novel feature of the proposed method is that it can include any number of alternative refrigerants and any number of quantitative and qualitative attributes simultaneously and aids in calculating the overall scores that assess the alternative refrigerants for the application considered. Using the simple linear scales that the method suggests, decision-makers may find it simpler to assign numerical values to the qualitative attributes. This fact is explained in the first case study presented. The third novel feature of the proposed method is that it does not require the use of fuzzy scales to transform qualitative attributes into quantitative attributes. The proposed method tackles the refrigerant selection problem holistically, or in its entirety, and is easy for decision-makers to put into practice. It may be understood that the proposed method offers a general decision-making methodology and is not meant for refrigerant selection only. The proposed methodology can be applied to a variety of selection problems in different fields of engineering and technology.

Acknowledgements

DST-SERB-MATRICS project number MTR/2023/000071.

References

- Poongavanam, G., Sivalingam, V., Prabakaran, R., Salman, M. Kim, S. C. Selection of the best refrigerant for replacing R134a in automobile air conditioning system using different MCDM methods: A comparative study, Case Studies in Thermal Engineering 27(2021), 101344.
- Prabakaran, R., Sivalingam, V., Kim, S. C., Poongavanam, G. K., Kumar, G. P. Future refrigerants with low global warming potential for residential air conditioning system: a thermodynamic analysis and MCDM tool optimization. Environmental Science and Pollution Research 29(2022), 78414–78428.
- Rao R.V. BHARAT: A simple and effective multi-criteria decision-making method that does not need fuzzy logic, Part-1: multi-attribute decision-making applications in the industrial environment. International Journal of Industrial Engineering Computations 15(2024a), 13-40.
- Rao R.V. BHARAT: A simple and effective multi-criteria decision-making method that does not need fuzzy logic, Part-2: role in multi- and many-objective optimization problems. International Journal of Industrial Engineering Computations 15(2024b), 1-12.
- Rao R.V. Decision making in the manufacturing environment using graph theory and fuzzy multiple attribute decision making methods -volume 2. Springer Verlag London (2013).
- Rao R.V. Phase change material selection using a simple and effective multi-attribute decision-making method. Archives of Thermodynamics (2024c) (Accepted).
- Rao R.V., Lakshmi, R. J. Selecting right alternatives in structural engineering problems using a simple and effective multi-attribute decision-making method. HCMCOU Journal of Science – Advances in Computational Structures (Under review).
- Saaty T. L. On the invalidity of fuzzifying numerical judgments in the analytic hierarchy process. Mathematical and Computational Modelling 46(2007), 962-975.
- Singh, A., Gupta, A., Bandhu, D., Kumari, S., Gupta, D. K., Kumar, A. Selection of refrigerants for domestic applications using MADM techniques. A book chapter in "Decision-making models and applications in

manufacturing environments", Apple Academic Press (2023) ISBN: 9781003394723.

- Souayeh, B., Bhattacharyya, S., Hdhiri, N., Alam, M.W. Selection of best suitable eco-friendly refrigerants for HVAC sector and renewable energy devices. Sustainability 14(2022), 11663.
    - Ustaoglu A., Kursuncu, B., Kaya, A. M., Caliskan, H. Analysis of vapor compression refrigeration cycle using advanced exergetic approach with Taguchi and ANOVA optimization and refrigerant selection with enviroeconomic concerns by TOPSIS analysis. Sustainable Energy Technologies and Assessments 52(2022),102182.

Declarations

Funding: DST-SERB-MATRICS project number MTR/2023/000071.

Potential competing interests: No potential competing interests to declare.