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HVAC Systems Evaluation and Selection for Sustainable Office Buildings: An Integrated MCDM Approach

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Abstract: Heating, Ventilation, and Air-Conditioning (HVAC) systems are critical components of maintaining an indoor air quality that ensures the thermal comfort of occupants in diverse building types. However, HVAC systems are also responsible for a substantial portion of the total energy consumption of commercial and industrial office buildings. This paper presents an integrated approach of two powerful MCDM techniques: the Best-Worst-Method (BWM) and The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) in order to evaluate and rank HVAC systems to ensure the best selection toward designing a sustainable office building. A set of conflicting criteria reported by international sustainable assessment centers were employed along with various HVAC systems to develop what is called herein a BWM-based TOPSIS model in order to conduct such a novel research attempt. Within the context of the investigated office building herein, the mini-package ductless system appears to be the best choice. This study could be further enhanced by including additional criteria and a larger sample size in future studies.

Keywords: HVAC; sustainability; office buildings; BWM; TOPSIS; MCDM

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1. Introduction

Heating, Ventilation, and Air-Conditioning (HVAC) systems are critical components of maintaining an indoor air quality that ensures the thermal comfort of occupants in diverse building types while simultaneously maintaining a high standard of indoor air quality [1–5]. Particularly in commercial and industrial office buildings, these systems are responsible for a substantial portion of the total energy consumption [6–10]. In some HVAC systems, the energy consumed by these systems is approximately between 30% to 50% of a building's total energy [11–16]. However, through the implementation of energy-efficient HVAC systems, it is possible to save up to 40% of this energy [17,18]. Thus, building size, occupancy level, and ventilation requirements can all influence the choice of HVAC system for an office building. It is also important to consider the energy efficiency, maintenance requirements, and cost of the system. A system that fails to consider these factors can cause excessive operating and maintenance costs and insufficient comfort and air quality. Therefore, there have been many regulatory and assessment centers established in recent years in order to promote sustainable buildings, as the demand for sustainable HVAC systems has increased dramatically. The most prominent of these centers include Building Research Establishment Environmental Assessment Methodology (BREEAM), Leadership in Energy and Environmental Design (LEED), Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB), The Global Sustainability Assessment System (GSAS), and Comprehensive Assessment System for Built Environment Efficiency (CASBEE). All of the methods mentioned above include several criteria, some of which overlap with others and some of which focus on specific aspects [19]. In light of conflicting criteria, the question that may arise here is "which HVAC system is the most appropriate for a sustainable office building?".

The novelty of this research lies in three dimensions. First, the context of the research is HVAC systems selection for Saudi office buildings. Although the research attempt herein

can be considered as an extension and continuation of the overall research efforts in handling HVAC systems issues generally [20–22], research works and applications dedicated to investigating such a context are still limited. Second, the selected methods are a dimension of the research. Although it is commonly known that within the MCDM field of research, various AHP methods have always been employed within TOPSIS applications to generate criteria weights [23–25], utilizing the BWM as a new technique, relatively, instead of AHP is an innovative approach by itself in this regard. Finally, national sustainable development initiatives such as the initiative of "Saudi Green" [26,27] as well as international commitments such as "the Kigali Amendment" [28,29] necessitate the need for any promising initiative and/or innovative application such as the conducted research attempt herein. Such attempts represent the road map via which the country will be capable of fulfilling the sustainability requirements at national and international levels, and also, the country will be able to facilitate attaining sustainable development goals in a consistent approach.

This paper presents an integrated approach of two powerful MCDM techniques: the Best-Worst-Method (BWM) and The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) in order to evaluate and rank HVAC systems to ensure the best selection toward designing a sustainable office building. A set of conflicting criteria reported by global and international sustainable assessment centers were employed along with various HVAC systems to develop what is called herein a BWM-based TOPSIS model in order to conduct such a novel research attempt. The rest of the paper is organized as follows: Section 2 presents an overview of previous studies that utilized MCDM within the context of HVAC system selection. Section 3 discusses the implementation of the BWM and TOPSIS in detail, along with their formulas and equations. The corresponding numerical phases of the selected case study are illustrated in Section 4. This study's findings are presented in the discussion section. The last section contains recommendations and conclusions.

2. Relevant Literature

Evaluation strategies in Heating, Ventilation, and Air Conditioning (HVAC) systems have received considerable attention in recent years by scholars. Multiple studies have evaluated and ranked the best HVAC system options for buildings using different evaluation methods, such as MCDM methods. Researchers have utilized a variety of MCDM techniques to evaluate and compare various HVAC alternatives. By using a fuzzy MCDM method, Alhakami [30] evaluated the effectiveness of HVAC systems for evaluating security risks. Moreover, value engineering, life cycle cost modeling, and MCDM were used by Al-Ghamdi and Al-Gahtani [31], as well as Kazemi and Mahdizadeh [32] for selecting HVAC systems that met sustainability criteria. An energy-efficiency, resilience, and sustainability framework for reinforced concrete buildings was proposed by Asadi et al. [33]. A similar overview of HVAC systems in buildings was provided by Asim et al. [34] and Feng et al. [35] in which the authors stressed the need to consider more than just energy efficiency when selecting HVAC systems.

The evaluation of HVAC systems has also been studied using specific methodologies. A hybrid simulation and MCDM framework was developed by Bac et al. [36] to determine the best HVAC system for an industrial building. Balasbaneh et al. [37] and Gan et al. [38] utilized multi-criteria decision making as part of their study on enhancing building sustainability in tropical climates. Other instruments have also been used alongside MCDM methods. As part of an early building's life cycle assessment, Forth et al. [39] established connected design decision networks.

Khadra et al. [40] applied weight factors to building renovation decisions using the Renobuild case study. MCDM techniques were used by Khadra et al. [40] to evaluate HVAC systems in renovation projects. In a study by Mokhtara et al. [41], Geographic Information System (GIS) and MCDM were used to optimize the design of plus-energy buildings in Algeria. Mokhtara et al. [41] investigated a number of HVAC system alternatives that were evaluated using MCDM methodologies, taking energy efficiency and environmental impact into account. Using fuzzy linguistic MCDM methods, Mukul et al. [42], Schito et al. [43],

and Li et al. [44] evaluated renewable energy options. Based on multiple energy-efficiency criteria and environmental sustainability criteria, the studies evaluated the suitability of various HVAC systems. The Weighted Point Method (WPM) was used by Prasanth et al. [45] to evaluate HVAC-AHU systems and the authors employed MCDM techniques to evaluate and rank various HVAC options based on performance and cost considerations.

Similarly, for a high-performance facade design, MCDM techniques have also been proposed by Moghtadernejad et al. [46] to improve building facade performance. A systematic approach was suggested by Moghtadernejad et al. [46] for integrating the various disciplines involved in the design of facades, including architecture, structural design, mechanical design, and electrical design, as well as a comprehensive action plan that takes into account all stages of the facade lifecycle. In addition to this, the Analytic Hierarchy Process (AHP) was found to be a useful method for selecting optimal options and evaluating outcomes for designing a high-performance facade [46]. Additionally, working with Choquet-based design methodologies and determining fuzzy metrics is useful for designing outside walls and building facades [37]. Pei Huang et al. [47] proposed an HVAC system design selection method by utilizing an MCDM approach under peak load forecast uncertainty. According to Pei Huang et al. [47] numerous studies have shown that this kind of prediction is uncertain because building physical parameters cannot be accurately set and weather conditions and internal loads differ from the actual situation after use. Due to its ability to directly incorporate uncertainty into the design, Pei Huang et al. [47] developed an MCDM framework that can be employed within the design stage to evaluate the performance of a design by analyzing multiple performance metrics and customer preferences. The Elimination Et Choix Traduisant la Realitè (Electre III) was also applied in order to evaluate and select the most suitable HVAC system to be installed in an office building considering criteria such as energy efficiency and user satisfaction [39].

Mahmoudi et al. [48] added a novel approach to the MCDM methods which aims to select and determine the performance of construction suppliers in light of the uncertainties after the COVID-19 pandemic, using the Fuzzy Ordinal Priority Approach (OPA-F). The OPA-A is one of the recent MCDM methods developed for determining the weights of criteria using fuzzy linguistic variables. It is worth noting that Mahmoudi et al. [49] applied the novel approach in the Supply Chain Finance (SCF) that supports the blockchain. Furthermore, the novel approach has been applied within the framework of Large-Scale Group Decision-Making (LSGDM) in healthcare management systems [50]. This approach has also been used in a combined manner with Data Envelopment Analysis (DEA) to evaluate suppliers' performance [51].

3. Methodology

This paper endeavors to assess the Heating, Ventilation, and Air Conditioning (HVAC) systems implemented in office buildings to support the sustainability of such structures. The sustainability of a building can be determined through various classifications that evaluate the effectiveness of the systems and designs in place, utilizing specific techniques and methodologies [19]. One such technique is the Multi-Criteria Decision-Making (MCDM) technique, which encompasses several methods. In this study, the Best-Worst-Method (BWM) and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method were combined to evaluate the HVAC systems for office buildings. Firstly, crucial criteria were identified based on previous studies reported in the literature. Secondly, HVAC experts assessed the weight of these criteria using the BWM technique. Finally, the HVAC systems were ranked using the TOPSIS technique.

The Best-Worst Method (BWM) is a relatively new yet powerful technique for solving MCDM problems, especially in determining the criteria's importance or weight [52]. Meanwhile, the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is a robust and fundamental method in the MCDM field that has gained widespread popularity and served as the foundation for developing many other methods [53,54]. With its versatil-

ity and broad applicability, TOPSIS has been used in various domains and applications [55]. As outlined by Rezaei [52], the BWM steps are explained as follows:

Step 1. The decision makers need to establish a set of evaluation criteria, which can be donated as $\{C_1, C_2, C_n\}$.

Step 2. Decision makers must identify and select the best criterion which is referred to as the influential or important criterion.

Step 3. Decision makers must identify and select the worst criterion which is referred to as the least important criterion.

Step 4. Assign a numerical value for the best criterion selected in step 2 ranging from one to nine against other criteria; therefore, the Best-to-Others vector is as follows: $A_{BO} = (a_{B1}, a_{B2}, \ldots, a_{Bn})$, where a_{Bj} denotes the preference of the best criterion C_B, over criterion $C_J, j = 1, \ldots, n$.

Step 5. Assign a numerical value for the worst criterion selected in step 3 ranging from one to nine against other criteria. The obtained Others-to-Worst vector is as follows: $A_{OW} = (a_{1W}, a_{2W}, a_{nW})$, where a_{jW} denotes the preference of criterion C_j over the worst criterion $C_W, j = 1, \ldots, n$.

Step 6. Calculate the weights (W_1^*, W_2^*, W_n^*) using the following model:

$$\underset{j}{Min\ Max} \left\{ \left| \frac{W_B}{W_j} - a_{BJ} \right|, \left| \frac{W_j}{W_W} - a_{JW} \right| \right\} \tag{1}$$

s.t

$$\sum_{j=1}^{n} W_J = 1, W_j \geq 0, \ for\ all\ j \tag{2}$$

Step 7. Check the consistency ratio. To assess the degree of consistency in an evaluation matrix, it is recommended to follow the steps outlined in Rezaei's paper [52]. A consistency ratio close to zero indicates a high level of consistency in the matrix, while a consistency ratio near one implies a lower level of consistency [56].

Based on BWM criteria weights, the TOPSIS method is used to rank alternative HVAC systems. TOPSIS technique is considered rational, and computationally efficient, and based on a simple mathematical formula, TOPSIS measures each alternative's relative performance using the following steps:

Step 1. Identify the decision matrix X, which can be represented as follows:

$$X = \begin{array}{c} \\ A_1 \\ A_2 \\ A_3 \\ \vdots \\ A_m \end{array} \begin{array}{c} \begin{array}{cccccc} B_1 & B_2 & B_3 & \ldots & B_n \end{array} \\ \begin{bmatrix} X_{11} & X_{12} & X_{13} & \ldots & X_{1n} \\ X_{21} & X_{22} & X_{23} & \ldots & X_{2n} \\ X_{31} & X_{32} & X_{33} & \ldots & X_{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ X_{m1} & X_{m2} & A_{m3} & \ldots & X_{mn} \end{bmatrix} \end{array} \tag{3}$$

where A_i designates the alternative HVAC system $i, i = 1, \ldots, m$: and B_j denotes the criteria $j, j = 1, \ldots,$ n. X_{ij} represents jth criteria with respect to ith alternative HVAC system.

Step 2. Identify the normalized decision matrix:

$$f_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}, i = 1, \ldots, m; \ j = 1, \ldots, n \tag{4}$$

Step 3. Identify the weighted normalized decision matrix which can be determined through multiplying the normalized decision matrix by the weight of the criterion. The weighted normalized decision matrix is expressed as:

$$v_{ij} = w_j f_{ij}, i = 1, \ldots, m; \ j = 1, \ldots, n \tag{5}$$

where w_j is the weight of the jth criterion. One advantage to using the BWM method is in its ability to utilize qualitative and quantitative information in defining the criteria weights.

Step 4. Identification of the positive-ideal and negative-ideal solutions through Equations (7) and (8) as follows:

$$Z^+ = \left\{v_1^+, v_2^+, \ldots, v_j^+\right\} = \left\{\left(max\ v_{ij} \middle| j \in I\right), \left(min\ v_{ij} \middle| j \in I'\right)\right\} \quad (6)$$

$$Z^- = \left\{v_1^-, v_2^-, \ldots, v_j^-\right\} = \left\{\left(min\ v_{ij} \middle| j \in I\right), \left(max\ v_{ij} \middle| j \in I'\right)\right\} \quad (7)$$

where A benefit criterion would be associated with I, and a cost criterion would be associated with I'.

Step 5. Evaluating each alternative's separation from the positive-ideal solution and the negative-ideal solution as follows:

$$S_i^+ = \left\{\sum_{j=1}^{n}\left(v_{ij} - v_j^+\right)^2\right\}^{\frac{1}{2}} \; i = 1, 2, \ldots, m; \; j = 1, 2, \ldots, \mathrm{n} \quad (8)$$

$$S_i^- = \left\{\sum_{j=1}^{n}\left(v_{ij} - v_j^-\right)^2\right\}^{\frac{1}{2}} \; i = 1, 2, \ldots, m; \; j = 1, 2, \ldots, \mathrm{n} \quad (9)$$

Step 6. Evaluate the relative closeness p_i of the positive-ideal solution as follows:

$$p_i = \frac{S_i^-}{S_i^+ + S_i^-}, i = 1, \ldots, m \quad (10)$$

The highest p_i value alternative is considered the optimal solution.

4. Application and Results

Through the process of building and office construction, HVAC systems influence a variety of factors directly associated with building design. As a result, choosing the right air conditioning system is essential for maintaining good indoor air quality, enhancing the working environment, reducing harmful environmental pollutants, and reducing energy consumption [57,58]. Since industrial factories, fuel vehicles, and power stations emit harmful emissions, as do some types of HVAC systems, it is necessary for decision makers to select a system that reduces carbon emissions in such a way that it achieves environmental, social, and economic sustainability [59].

This paper proposes an approach of integrated MCDM methods to rank the HVAC systems based on their sustainability. All criteria included in this study are presented in Table 1. The criteria were selected based on their presence in the global evaluation systems such as The Leadership in Energy and Environmental Design (LEED) [60], British Building Research Establishment Environmental Assessment Method (BREEAM), Deutsches Gütesiegel Nachaltiges Bauen (DGNB), Global Sustainability Assessment System (GSAS), and Comprehensive Assessment System for Built Environment Efficiency (CASBEE).

A group of experts with a mechanical engineering background were involved to obtain their opinions as inputs to the developed BWM model. They were experts in air-conditioning systems and held executive-level positions within the field of building maintenance and management. Most of the involved experts belong to international companies within the field of HVAC systems. Some experts were working in dynamic sectors/industries such as the aviation sector, in which buildings are huge and require top niche expertise to maintain the highest level of operations and services. Opinion extraction exercises such as the developed BMW model herein ensured the reliability of the collected data. Details on the mathematical steps are discussed above in Section 3.

Table 1. Most important criteria selected for this study to rank alternative HVAC systems.

Criteria		Sub-Criteria		LEED	BREEAM	DGNB	GSAS	CASBEE
Environmental	(C1)	Energy Consumption	(C11)	√	√	√	√	√
		CO_2 Emission	(C12)	√	√	√	√	√
		Noise Level	(C13)	√	√	√		√
Economical	(C2)	Capital Cost	(C21)			√		
		Maintenance Cost	(C22)			√		
		Lifetime	(C23)			√		√
Socio-Functional	(C3)	Ventilation	(C31)	√	√	√	√	√
		Thermal Comfort	(C32)	√	√	√	√	√
		Indoor Volume Requirement	(C33)			√	√	
		Indoor Appearance	(C34)			√	√	
		Outdoor Appearance	(C35)	√	√	√	√	
Technical	(C4)	Ease of Installation	(C41)					√
		Ease of Maintenance	(C42)			√		√
		Vendor Availability	(C43)					√

The feedback of decision makers about the selection of nine HVAC systems for office buildings in Saudi Arabia was based on finding energy and cooling-efficient systems that can adapt to the hot climates of the region where temperatures often reach extreme levels. Furthermore, it was based on creating a productive environment by optimizing comfort and indoor air quality that is aligned with sustainability goals. Further details in this regard are presented in Table 2.

Table 2. The nine alternatives of the HVAC systems.

Alternative	Other Known Names and/or Abbreviation	Description and Selection Justification
Mini-Package Unit	Window Air Conditioner (AC)	It is a compact and self-contained HVAC system installed in windows or wall openings. It cools the air by absorbing heat and condensing moisture, and can also provide heating in winter using a reverse cycle function or heat pump.
Roof Top Unit	RTU	It is a packaged HVAC system installed outside or on the rooftop of buildings that combines heating, cooling, and ventilation components in a single package, using ductwork to distribute conditioned air throughout the building. RTUs can provide both heating and cooling to the entire building or specific zones, depending on their design and capacity.
Mini-Split	Ductless heating (also known as mini-splits, a ductless heat pump, or mini-split AC)	It is a ductless mini-split HVAC system consisting of an outdoor unit and indoor units, providing efficient cooling. The outdoor unit extracts or releases heat from the outdoor air, while the indoor units are installed in specific areas or rooms, allowing personalized temperature control for enhanced comfort and energy efficiency.
Condensing Unit connected to an Air Handling Unit	Condensing Unit connected to AHU	The HVAC system comprises a condensing unit connected to an air handling unit (AHU). The condensing unit, located outside the building, releases heat to transform Freon refrigerant into a liquid state and sustains the cooling cycle. The AHU circulates and conditions air through filters, heating or cooling coils, and a fan, ensuring even airflow throughout the building.

Table 2. *Cont.*

Alternative	Other Known Names and/or Abbreviation	Description and Selection Justification
Condensing Unit connected to a Fan Coil Unit	Condensing Unit connected to FCU	The HVAC system consists of a condensing unit connected to a fan coil unit (FCU). The condensing unit, located outside the building, transforms refrigerant from vapor to liquid by releasing heat, while the FCU, typically installed indoors, regulates temperature by drawing in return air, adjusting its temperature through the heating or cooling coil, and distributing conditioned air back into the space using its fan.
The Variable Refrigerant Flow (VRF) System connected to Air Handling Unit	VRF connected to AHU	This system is an advanced HVAC technology that provides versatile cooling and heating. It uses refrigerant for heat exchange and consists of an outdoor unit with a compressor and condenser, connected to an AHU that filters and delivers conditioned air to the building's interior areas.
The Variable Refrigerant Flow System connected to Fan Coil Unit	VRF connected to FCU	This system offers efficient cooling and heating with precise temperature control and energy efficiency. The VRF system modulates refrigerant flow and temperature to each FCU based on specific requirements, while the FCU utilizes the conditioned refrigerant to distribute comfortable air to the space.
Air-Cooled Chilled Water connected to Air Handling Unit	Air-Cooled Chilled Water connected to AHU	This system utilizes chilled water for cooling. It includes a chiller, pumps, and piping to circulate the chilled water. The AHU, responsible for air distribution, draws in return air, filters it, and passes it over the cooling coils, where it is cooled by the chilled water before being distributed back into the space.
Air-Cooled Chilled Water connected to a Fan Coil Unit	Air-Cooled Chilled Water connected to FCU	This system utilizes chilled water for effective cooling and air distribution. The system includes a chiller, pumps, and piping to circulate chilled water, while the FCU consists of a fan, cooling coil, filters, and controls. The chilled water flows through the cooling coil in the FCU, cooling the air that is then circulated throughout the building, ensuring comfortable indoor temperatures.

Mechanical consultant experts in HVAC design were provided with the comparison evaluation matrix to assign the evaluation score from 1 to 9 as shown in Table 3. Further details are also presented in Tables 4 and 5.

Based on the experts' evaluation, Tables 4 and 5 present the Best-to-Others and Other-to-Worst values, respectively. Based on the experts' evaluations, the environmental criterion is the most important main criterion (best criterion).

Table 3. Evaluation score for BWM technique.

Verbal Judgment	Numeric Value
Absolutely more important	9
Somewhat between Very strong and Absolute	8
Very strongly more important	7
Somewhat between Strong and Very strong	6
Strongly more important	5
Somewhat between Moderate and Strong	4
Moderately more important	3
Somewhat between Equal and Moderate	2
Equally important	1

Table 4. Best-to-Others vectors obtained by the expert evaluations.

Best-to-Others						
Main Criteria	C1	C2	C3	C4		
C1	1	2	5	4		
Sub-Criteria C1	C11	C12	C13			
C12	3	1	5			
Sub-Criteria C2	C21	C22	C23			
C21	1	3	4			
Sub-Criteria C3	C31	C32	C33	C34	C35	C36
C35	3	2	2	7	1	5
Sub-Criteria C4	C41	C42	C43			
C43	5	2	1			

Table 5. Others-to-Worst vectors obtained by the expert evaluations.

Main Criteria	**C3**
C1	5
C2	4
C3	1
C4	2
Sub-Criteria C1	C13
C11	2
C12	5
C13	1
Sub-Criteria C2	C23
C21	4
C22	2
C23	1
Sub-Criteria C3	C34
C31	4
C32	5
C33	4
C34	1
C35	7
C36	3
Sub-Criteria C4	C41
C41	1
C42	3
C43	5

Using the BWM pairwise comparisons, Table 5 illustrates the Others-to-Worst values. The least influential main criterion was the socio-functional criterion. On the other hand, the best criterion within the environmental aspect was the level of CO_2 emissions while the least criterion was the noise level. For the economic aspect, the capital cost was the best criterion and the lifetime was the least criterion. The indoor appearance was the best criterion within the socio-functional main criterion and the outdoor volume was the least one. Lastly, the vendor availability was the best criterion within the technical main criterion and the ease of installation was the least criterion. All consistency levels of the evaluation matrixes were acceptable and within the range. The weight as well as the feature of each criterion is presented in Table 6.

Table 6. Criteria and sub-criteria BWM weights.

Criteria	Sub-Criteria	Weight	Overall-Weight	Feature
C1		0.494		
	C11	0.225	0.111	Cost
	C12	0.650	0.321	Cost
	C13	0.125	0.061	Cost
C2		0.279		
	C21	0.628	0.176	Cost
	C22	0.228	0.064	Benefit
	C23	0.142	0.040	Benefit
C3		0.086		
	C31	0.132	0.011	Benefit
	C32	0.198	0.017	Benefit
	C33	0.198	0.017	Cost
	C34	0.042	0.004	Cost
	C35	0.348	0.030	Benefit
	C36	0.079	0.000	Benefit
C4		0.139		
	C41	0.111	0.016	Benefit
	C42	0.305	0.043	Benefit
	C43	0.583	0.082	Benefit

As indicated earlier, the goal of this paper is to rank the HVAC systems using the MCDM technique based on several important criteria which have been reported in global evaluation assessments. There are nine alternatives involved in this study which include Mini-Package Ductless (A1), Roof Top Unit Duct (A2), Mini-Split Ductless (A3), Condensing Unit Connected to AHU (A4), Condensing Unit Connected to FCU (A5), VRF Connected to AHU (A6), VRF Connected to FCU (A7), Air-Cooled Chilled Water Connected to AHU (A8), and Air-Cooled Chilled Water Connected to FCU (A9). The data used in this paper are presented in Table 7 along with the criteria and the alternatives. The data was standardized in order to obtain the normalized decision matrix which can be identified by multiplying the global criteria weights with the normalized decision matrix as shown in Table 8.

Table 7. Decision matrix for TOPSIS method.

Alt. #	C11	C12	C13	C21	C22	C23	C31	C32	C33	C34	C35	C36	C41	C42	C43
A1	554	315	65	184,788	4	10	1	1	1.77	23.30	1	1	5	5	5
A2	656	373	60	392,679	3	15	2	4	0.00	103.06	5	3	3	3	4
A3	1299	739	50	248,184	4	10	1	2	10.10	27.77	3	4	4	4	5
A4	893	508	60	808,500	2	20	2	4	13.12	51.21	5	3	2	2	3
A5	873	496	55	475,260	3	15	1	3	22.60	51.21	4	4	3	3	4
A6	1840	1047	60	1,500,000	2	20	2	4	15.74	15.29	4	3	2	2	3
A7	1832	1043	55	899,964	3	15	1	3	21.46	15.29	4	5	3	3	4
A8	405	230	60	910,000	2	25	2	4	2.19	30.06	5	3	1	1	3
A9	380	216	55	859,000	3	20	1	3	23.52	30.06	4	2	2	2	3

Alt. # = alternative number.

Table 8. Weighted normalized decision matrix.

Alt. #	C11	C12	C13	C21	C22	C23	C31	C32	C33	C34	C35	C36	C41	C42	C43
A1	0.019	0.054	0.023	0.014	0.029	0.008	0.002	0.002	0.001	0.001	0.002	0.001	0.009	0.024	0.035
A2	0.022	0.064	0.021	0.029	0.021	0.012	0.005	0.007	0.000	0.003	0.012	0.002	0.005	0.014	0.028
A3	0.044	0.126	0.018	0.018	0.029	0.008	0.002	0.003	0.004	0.001	0.007	0.003	0.007	0.019	0.035
A4	0.030	0.086	0.021	0.059	0.014	0.015	0.005	0.007	0.005	0.001	0.012	0.002	0.003	0.009	0.021
A5	0.029	0.084	0.020	0.035	0.021	0.012	0.002	0.005	0.009	0.001	0.010	0.003	0.005	0.014	0.028
A6	0.062	0.178	0.021	0.110	0.014	0.015	0.005	0.007	0.006	0.000	0.010	0.002	0.003	0.009	0.021
A7	0.061	0.177	0.020	0.066	0.021	0.012	0.002	0.005	0.008	0.000	0.010	0.003	0.005	0.014	0.028
A8	0.014	0.039	0.021	0.067	0.014	0.019	0.005	0.007	0.001	0.001	0.012	0.002	0.002	0.005	0.021
A9	0.013	0.037	0.020	0.063	0.021	0.015	0.002	0.005	0.009	0.001	0.010	0.001	0.003	0.009	0.021

Alt. # = alternative number.

The ranking of alternative HVAC systems is identified by using Equations (6)–(8). The evaluation of the final ranking is represented in Table 9. Based on the outcome result, the best alternative is the Mini-Package Ductless (A1) with P_i value of 0.8521 followed by the Roof Top Unit Duct (A2) with P_i value of 0.8025. The rest of the ranking result is shown in Table 9.

Table 9. The final evaluation and ranking of alternatives.

Alternative	S^+	S^-	P_i	Rank
A1	0.0287	0.1652	0.8521	1
A2	0.0363	0.1473	0.8025	2
A3	0.0965	0.1095	0.5316	7
A4	0.0730	0.1114	0.6039	6
A5	0.0579	0.1255	0.6843	5
A6	0.1793	0.0199	0.0999	9
A7	0.1588	0.0474	0.2297	8
A8	0.0587	0.1549	0.7251	4
A9	0.0551	0.1574	0.7408	3

5. Discussion

Inefficient office buildings' designs have always challenged practitioners and engineers to create innovative and affordable solutions to ensure better and more effective office buildings' operations; hence, the integration of different energy conservation strategies in parallel has recently resulted in a significant reduction in the total energy consumption (i.e., 26.81%) [61].

Undoubtedly, solving the dilemma of selecting the most appropriate HVAC systems considering various conflicted criteria [31], as implemented in this paper, represents one of the critical forward steps toward practical implementation of the Saudi building code [62], sustainable commitment to international agreements in this regard such as the Kegali agreement [28], and attaining the ultimate goals of the promising initiatives such as the Saudi Green Initiative [26].

To select an HVAC system for a sustainable office building, this paper presents an integrated method of BWM and TOPSIS which is a practical and effective option. Using a pairwise comparison, the BWM method calculates the weight of each of the 15 criteria. Using the TOPSIS method, nine alternatives of HVAC systems are ranked according to their performance on the criteria. Weights obtained by using the pairwise comparison play a decisive role in selecting the most appropriate HVAC system.

For any office environment to be pollution-free, it is necessary to have adequate outdoor air provided by the HVAC system. One of the most important criteria taken into consideration when selecting the HVAC systems for a sustainable office building is CO_2 emissions, which constitute 32% of the decision making based on the weights calculated by the BWM method in this study. Therefore, due to the global increasing demand for energy and the need to reduce carbon emissions, selecting an HVAC system has become a crucial part of building design. Numerous studies have shown how important it is to reduce the percentage of CO_2 in buildings [63], which reinforces the importance of choosing the most appropriate HVAC system. In a study by Perdamaian et al. [64] and another one by Parker et al. [65], the authors have demonstrated that HVAC interventions can reduce carbon dioxide emissions. In this study, the data obtained indicated that a mini-package ductless system would be the best option for sustainable office buildings. As mentioned earlier, CO_2 emission was a significant factor in the choice, accounting for 32% of the decision. Figure 1 depicts the CO_2 emissions from each alternative examined in this paper, and the mini-package ductless (A1) is among the top three alternatives in low CO_2 emissions.

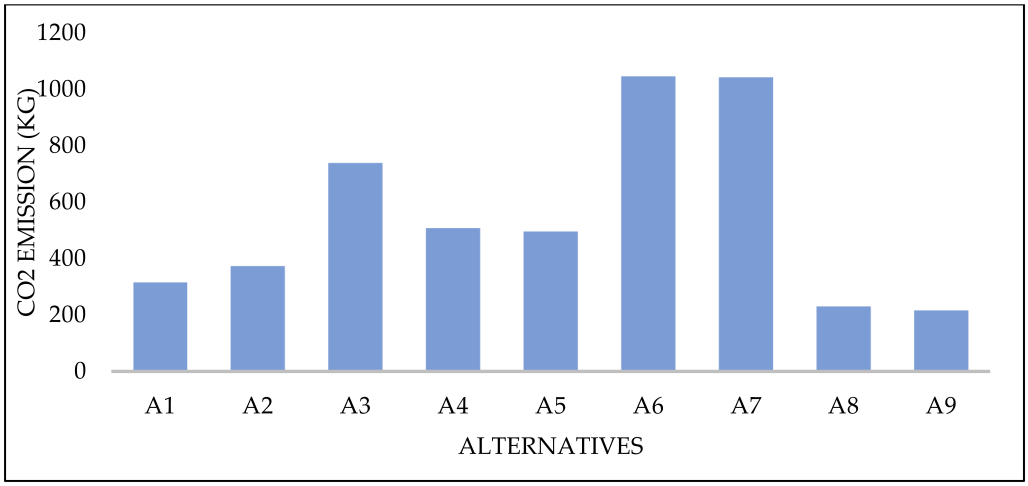


Figure 1. CO_2 emissions for each alternative.

Another very important factor in decision making is based on the opinion of experts of this study which is the capital cost that constitutes 17% of decision making in choosing the most appropriate HVAC system for sustainable office buildings. Furthermore, experts put the energy consumption criterion in third place with 11% of the decision making, which makes the criterion one of the most important and decisive criteria in ranking the preference of HVAC systems in sustainable office buildings.

Figure 2 shows the energy consumption for each alternative included in this study. Due to the sophisticated and advanced technologies used in the manufacture of the mini-package ductless (A1) system, it is among the least energy-consuming systems on the market.

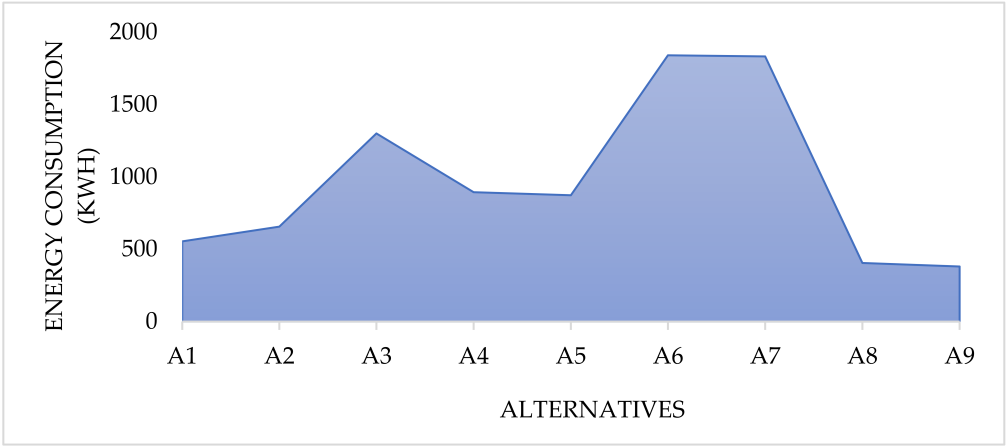


Figure 2. Energy consumption for each alternative.

There is an 8% weighting given to vendor availability in the decision-making process. Due to the fact that system and spare part availability in the market depends on the availability of vendors, this criterion also incorporates the brand image, references, and licenses of brands, the availability of their local vendors, and the risks associated with importing a system if it is not available in the country [66]. The data obtained indicate that most of the systems are available on the market and the number of vendors for alternatives is similar. The rest of the remaining criteria in this study were of varying weights between 1% and 6%. As a result of considering all conflict criteria involved in this study, the mini-package ductless (A1) is determined to be the best alternative using two integrated MCDM methods for the HVAC system installation in office buildings.

The preference between the best and worst alternative is because the mini-package ductless, as a self-contained unit, provides efficient cooling and heating for spaces, achiev-

ing energy efficiency and effective temperature control through careful selection and sizing. Its simplicity of design minimizes energy losses and enhances overall system performance. Additionally, the mini-package ductless offers advantages such as ease of installation, cost efficiency, and space efficiency due to its compact nature. In contrast, VRF connected to AHU has disadvantages including higher initial costs, complex installation and maintenance, space limitations, and potential refrigerant leakage.

6. Conclusions

As sustainability becomes a key focus in the construction industry, the evaluation of HVAC systems is critical in office building design. The concept of sustainability refers to meeting the needs of the present without compromising the ability of future generations to meet the needs of the future. A sustainable office building reduces its environmental impact, promotes energy efficiency, promotes occupant comfort and well-being, and considers the long-term viability of the enterprise. By minimizing resource consumption and reducing environmental harm, sustainable office buildings provide a healthy and productive work environment. There are various rating systems used to assess the sustainability of office buildings, including BREEAM, CASBEE, DGNB, LEED, and GSAS. In these rating systems, specific criteria and standards are used to evaluate and certify the sustainability of buildings. In the presence of many conflicting criteria that need to be considered and evaluated, this study aims to rank HVAC systems for a sustainable office building using a combined MCDM approach. Using the combined BWM and TOPSIS methods in this study, decision makers are equipped with a valuable tool for selecting the best alternative for HVAC systems during the design phase. Among the other options for implementing HVAC systems in office buildings to support sustainability, the mini-package ductless system appears to be the best choice. This study could be further enhanced by including additional criteria and a larger sample size in future studies. As a result of this study, decision makers and designers of office buildings will be able to gain valuable insights into the selection process for HVAC systems using an MCDM integrated approach.

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