INTERNATIONAL JOURNAL OF CONSTRUCTION MANAGEMENT
https://doi.org/10.1080/15623599.2020.1742638

Selection of HVAC-AHU system supplier with environmental considerations using Fuzzy EDAS method

Gul Polat[a] and Hasan Gokberk Bayhan[b]

[a]Department of Civil Engineering, Faculty of Civil Engineering, Istanbul Technical University, Istanbul, Turkey; [b]Department of Civil Engineering, Faculty of Technology, Sakarya University of Applied Sciences, Sakarya, Turkey

ABSTRACT
Buildings, but especially commercial buildings, are mainly responsible for the energy consumption and greenhouse gas emission. Although energy consumption profiles may vary, heating, ventilating and air conditioning (HVAC) systems and lighting are the major energy users in buildings. HVAC systems constitute several parts and the air handling unit (AHU) is one of the most important components as it uses a significant amount of the energy and its initial cost is relatively higher than the other parts. Therefore, selecting the most appropriate HVAC-AHU system and its supplier plays a significant role in improving the energy efficiency of air-conditioned buildings and thereby obtaining a good score from the green certification system according to which the project in question is evaluated. In general, multiple decision makers, who may have different viewpoints and prefer to express their evaluations by linguistic terms, are in charge of selecting the proper HVAC-AHU system and its supplier from several possible alternatives considering numerous compromising and conflicting criteria simultaneously. This paper employs fuzzy Evaluation Based on Distance from Average Solution (Fuzzy EDAS) method for solving the HVAC-AHU system and its supplier selection problem for a green multifunctional shopping centre project located in Moscow. After obtaining the results and determining the optimal solution, sensitivity analysis was carried out to show the stability of the results. The decision makers found the method applicable and practical.

KEYWORDS
Multi-attribute-decision-making; Fuzzy evaluation based on distance from average solution (Fuzzy EDAS); green buildings; HVAC-AHU systems; supplier selection; case study

Introduction

Construction industry has crucial environmental, social and economic influences on the society. While some of these impacts are positive, others are negative. The positive impacts consist of delivering buildings and facilities to fulfil people's needs and demands, creating direct or indirect employment opportunities, contributing to the national economies, and playing a critical role in urbanization. On the other hand, the negative impacts can be categorized in two groups, which are: 1) the noise, dust, traffic congestion, water pollution, waste disposal, natural soil tissue and vegetation destruction, blockage of drainage water, and consumption of huge amount of natural resources during the construction stage and 2) the energy consumption and greenhouse gas emission for which the buildings are responsible (Széll 2003; Zuo and Zhao 2014; Doan et al. 2017; Goudarzi and Mostafaeipour 2017). Indeed, the negative impact of the construction industry on the environment can be justified by the production of 35–40% of CO_2 emissions, the consumption of 40% of raw materials and 25% of timber, the production of 40% of solid waste, the consumption of 40% of total energy and 70% of electricity, and the usage of 16% of water worldwide (Yüksek, 2015; Durdyev et al. 2018; Baniassadi et al. 2018).

As a result of these negative impacts on the environment, today, the idea of green building is a requirement, not an option. Green building has been defined as a practice of 1) increasing the efficiency of energy, water, and materials usage in buildings and their sites, and 2) reducing the impacts of buildings on human health and the environment via better sitting, design, construction, operation, maintenance, and removal the whole building life cycle (Ghodrati et al. 2012). The US Green Building Council (USGBC) defines green building as 'the practice of increasing the efficiency of new buildings, and reducing their impact on human health and the environment through better site location, design, construction, operation, maintenance, and removal'. Based on these definitions, it can be interpreted that green building is the product of sustainable and innovative design, which focuses on improving the efficiency of resource use – energy, water, and materials – while decreasing the impacts of buildings on human health and the environment (e.g., thermal comfort, better ventilation, using more sunlight, acoustic, higher indoor air quality, lower CO_2 emissions, etc.) during their life-cycle (Dwaikat and Ali 2016; El-Sayegh et al. 2019). Less impact on human health and the environment is one of the main features of green buildings.

In order to identify a building as 'green', it should be certified (Ampratwum et al. 2019). There are many recognized green building certification systems all around the world. Different countries have developed their own green building certification systems, while other countries adopt these ones. Some of the widely used certification systems are: Leadership in Energy and Environmental Design (LEED), Building Research Establishment Environmental Assessment Method (BREEAM), Green Star, Deutsche Gesellschaft für Nachhaltiges Bauen e.V. (DGNB), Comprehensive Assessment System for Built Environment Efficiency (CASBEE), The International Initiative for a Sustainable Built Environment (IISBE), etc. (Doan et al. 2017; Akcay and Arditi 2017).

CONTACT Gul Polat polatgu@itu.edu.tr

Commercial buildings are classified amongst the buildings, which consume the highest energy (Gul and Patidar 2015). Thus, the commercial building sector plays a significant role in achieving more sustainable development (Azar and Menassa 2012). Therefore, constructing energy efficient buildings, which have proper building envelop materials including insulation types, roofing materials, finishing materials, window type, size, and glazing, to ensure thermal comfort, are equipped with lighting and HVAC systems that have optimal energy performance level, have intelligence to optimize energy usage, and maintain renewable and non-polluting energy sources, is crucial.

Energy consumption profiles may vary but heating, cooling and lighting are the major energy users in buildings, but especially in commercial buildings (Garnier et al. 2015). HVAC systems play a critical role in achieving the thermal comfort and indoor air quality at residential and non-residential buildings (Yuwono et al. 2015). Since they consume a major portion of the energy delivered to buildings, they are considered as a potential candidate for improving the energy efficiency of air-conditioned buildings (Fasiuddin et al. 2010). Indeed, HVAC systems account for nearly 60% of the total energy consumption of commercial buildings (Carreira et al. 2018). HVAC systems constitute several parts and AHU is one of the most important components as it uses a significant amount of the energy (Kusiak and Li 2010; Kusiak et al. 2010) and its initial cost is relatively higher than the other parts (Aktacir et al. 2010). Therefore, selecting the most appropriate HVAC-AHU system and thereby its supplier with environmental considerations plays a significant role in obtaining a good score from the certification system according to which the project in question is evaluated.

In the traditional supplier evaluation/selection approach, the most important aspect was the cost, which cannot guarantee that the selected supplier is global optimal as the customer-oriented criteria (e.g., quality, delivery performance, reputation, flexibility, service, management, relationship, risk, safety, technology, research and development, manufacturing capability, performance history, etc.) were not taken into account. In the contemporary supply management approach, cost was not the most widely adopted criterion, the customer-oriented criteria have gained importance (Aretoulis et al. 2010; Ho et al. 2010). Nowadays, companies consider the environmental aspects when selecting their suppliers as well as cost and the aforementioned customer-oriented criteria (Amindoust et al. 2012; Rao et al. 2017).

In most construction projects, multiple decision makers, who have different points of views, aim to select the most appropriate supplier among a set of possible alternatives with different levels of capabilities and potential (Plebankiewicz and Kubek 2016; Luzon and El-Sayegh 2016). Besides, several compromising and conflicting criteria are taken into account at the same time. Therefore, supplier selection problem should be treated as a multi-criteria-group-decision-making (MCGDM) problem. In most of the real life problems, it is very difficult for decision makers to evaluate the possible alternatives according to the determined criteria with exact numerical values as the information is often uncertain and/or their thoughts may be imprecise. In such cases, decision makers may prefer to make their evaluations by linguistic variables in which words or sentences in a natural or artificial language is used, and provide interval judgments rather than fixed value judgments (Zadeh 1975). In this context, fuzzy set theory is a powerful tool for reaching sound decisions where uncertainty and incomplete information exist (Wong and Lai 2011). Therefore, the fuzzy set theory is commonly integrated with multi-criteria-decision-making (MCDM) methods in order to make the evaluation process more flexible and suitable for decision makers' imprecise nature of evaluations and judgments (Kahraman et al. 2010).

Green certification development has a relatively short history in Russia. On December 30, 2009, the Federal Law No.385-FZ allowed changes in the existing technical regulations and usage of foreign legislation such as BREEAM and LEED green building standards in the Russian Federation (Porfiriev et al. 2017). Green building technologies are mostly used in the construction of commercial buildings in Russia (Kondrachuk and Petrenko 2015). Comcity (LEED Gold), K2 Business Park (BREEAM Excellent), Arcus III (BREEAM Very Good), Vivaldi Plaza (BREEAM Good) are some of the examples of green commercial buildings in Moscow. There are 48 projects listed for LEED certification (USGBC, 2019) and 85 projects listed for the BREEAM certification system in Moscow (BRE 2019). In addition to the usage of BREEAM and LEED standards, there is a national standard for environmental certification of real estate in Russia named 'Green Standards', which has been implemented since 2011. 'Green Standards' include the following sections: environmental management; site selection, infrastructure and landscape arrangement; water management, regulation of storm water runoff and pollution prevention; architectural planning and design solutions; energy saving and energy efficiency; materials and waste; habitat quality and comfort; and life safety (Sirazetdinov et al. 2018).

In this paper, the fuzzy EDAS method was applied for solving the HVAC-AHU system and its supplier selection problem in the studied project. The main objective of this study is to make a decision on selecting the most appropriate HVAC-AHU system and its supplier for a green construction project, namely the multifunctional shopping center project located in Moscow, taking into account the uncertainties and inaccuracies inherent in the supplier selection process. The studied project was awarded for 'Green Standards - Gold' certification level.

The main reason for applying this method is that the fuzzy EDAS method allows for both calculating the criteria weights and ranking the alternatives in a simple and easy way. If other MCGDM methods such as fuzzy COPRAS, fuzzy ARAS, etc. were chosen, they should have been integrated with the criteria weighting methods such as AHP, DEMATEL, etc., which would complicate the problem (Stević et al. 2018). The traditional EDAS method and its different forms have been successfully implemented in various fields such as assessment of stairs shape for dwelling houses (Turskis and Juodagalvienė 2016), supplier selection (Keshavarz Ghorabaee et al. 2016), solid waste disposal site selection (Kahraman et al. 2017), supplier evaluation and order allocation with environmental considerations (Keshavarz Ghorabaee et al. 2017a), performance evaluation of bank branches (Keshavarz Ghorabaee et al. 2017b), assessment of a healthy and safe built environment according to sustainable development principles (Zavadskas et al. 2017), ranking of cultural heritage structures for renovation projects (Turskis et al. 2017), third party logistics provider (Ecer 2018), valuation of house's plan shape (Juodagalvienė et al. 2017), evaluation of quality assurance in contractor contracts (Trinkūnienė et al. 2017), evaluation of construction equipment with sustainability considerations (Keshavarz Ghorabaee et al. 2018), selection of carpenter manufacturer (Stević et al. 2018), etc.

Previous studies on HVAC system selection

The previous studies focusing on decision-making process for HVAC system selection are summarized below.

Avgelis and Papadopoulos (2009) develops a method, which uses the multi-criteria decision-making and the building simulation, for choosing and managing HVAC systems in new and existing buildings.

Bichiou and Krarti (2011) developed a comprehensive energy simulation environment for selecting both building envelope features and heating and air conditioning system design and operation settings, which minimizes the life cycle costs.

Chinese et al. (2011) employed Analytic Hierarchy Process (AHP) method for selecting space heating systems for an industrial building. In this study, the technologies available for industrial heating are discussed, evaluation/selection criteria are elicited from the decision maker, and the alternatives are ranked using the developed AHP model.

Kim et al. (2014) presented a multi-criteria, namely construction cost and total energy consumption, decision making of HVAC systems under uncertainty using Bayesian Markov chain Monte Carlo method. In this study, a library building was selected and modelled using EnergyPlus 6.0.

Huang et al. (2015) proposed a prototype of HVAC system design under uncertainty, which considers uncertainty in the design phase assesses the performance of a design in terms of multiple performance indices and the customers' requirements and preferences.

Arroyo et al. (2016) presented a detailed case study of choosing an HVAC system for a net zero energy building in California using choosing by advantages (CBA) method. This study reveals that CBA supports the selecting problem by integrating multiple perspectives, creating transparency, separating 'value' from cost, and clearly documenting the decision in a rational way.

Yang et al. (2016) proposed a framework, which quantitatively evaluates the energy implications of occupancy diversity at the building level. Building information modeling (BIM) is integrated to the proposed framework in order to obtain building geometries, HVAC system layouts, and spatial information as inputs for computing potential energy implications.

Ascione et al. (2017) proposed a new comprehensive approach that supports cost-optimal design of building envelope's thermal characteristics and HVAC systems in presence of a simulation-based model predictive control for heating and cooling operations.

Ghahramani et al. (2017) developed a model-free control policy that begins learning optimal settings with no prior historical data and optimizes HVAC operations through finding optimal set points at the building level and controlling set points accordingly.

Previous studies mostly aim to either optimize the operation HVAC systems or design the HVAC systems. This study distinguishes from the aforementioned studies as it tries to solve the problem of HVAC-AHU system and its supplier selection and it employs fuzzy multi-attribute-decision-making technique, namely fuzzy EDAS.

Mathematical background

In this section, the principles of fuzzy set theory and fuzzy EDAS methodology will be briefly explained.

Fuzzy set theory

Fuzzy set theory was first introduced by Zadeh (1965). The elements in fuzzy sets have been defined by their degrees of membership, whereas the membership of elements in a classical set is defined in binary terms, which means that an element either belongs or not belong to the set. The fuzzy set theory and its applications enable decision makers to deal with uncertainties and vagueness in an effective way (Dixit et al. 2018; Roghanian et al. 2018). There are different types of fuzzy numbers such as triangular, trapezoidal, Gaussian, etc. In this study, trapezoidal fuzzy numbers are used as they are extensively along with the triangular fuzzy numbers (Ebadi et al. 2013).

A trapezoidal fuzzy number (TFN) ($\tilde{A}$) is defined by four crisp numbers expressed as a quadruplet (a_1, a_2, a_3, a_4), and its membership function ($\mu_{\tilde{A}}(x)$) whose values can be any number in the interval [0, 1], where 0 means that the value (x) does not belong to the set in question and 1 means that the value (x) completely belongs to the set.

Some of the definitions related to fuzzy sets and numbers are stated below (i.e., Keshavarz Ghorabaee et al. 2016; Stević et al. 2018):

The membership function ($\mu_{\tilde{A}}(x)$) of a fuzzy number $\tilde{A}$ (a_1, a_2, a_3, a_4) can be expressed as in Eq. (1):

$$\mu_{\tilde{A}}(x) = \begin{cases} (x-a_1)/(a_2-a_1) & a_1 \le x \le a_2 \\ 1 & a_2 \le x \le a_3 \\ (a_4-x)/(a_4-a_3) & a_3 \le x \le a_4 \\ 0 & otherwise \end{cases} \quad (1)$$

An example of a TFN is shown in Figure 1.

A crisp number k can be represented by a TFN $\tilde{k} = (k, k, k, k)$.

The arithmetic operations of two positive TFNs $\tilde{A} = (a_1, a_2, a_3, a_4)$ and $\tilde{B} = (b_1, b_2, b_3, b_4)$, where $a_1 \ge 0$, $b_1 > 0$ and k is a crisp number, are displayed in Eqs. (2)–(9) (i.e., Keshavarz Ghorabaee et al. 2016; Stević et al. 2018):

Addition:

$$\tilde{A} \oplus \tilde{B} = (a_1 + b_1, a_2 + b_2, a_3 + b_3, a_4 + b_4) \quad (2)$$

$$\tilde{A} + k = (a_1 + k, a_2 + k, a_3 + k, a_4 + k) \quad (3)$$

Subtraction:

$$\tilde{A} \ \theta \ \tilde{B} = (a_1 - b_1, a_2 - b_2, a_3 - b_3, a_4 - b_4) \quad (4)$$

$$\tilde{A} - k = (a_1 - k, a_2 - k, a_3 - k, a_4 - k) \quad (5)$$

Multiplication:

$$\tilde{A} \otimes \tilde{B} = (a_1 \times b_1, a_2 \times b_2, a_3 \times b_3, a_4 \times b_4) \quad (6)$$

$$\tilde{A} \times k = \begin{cases} (a_1 \times k, a_2 \times k, a_3 \times k, a_4 \times k) & if \quad k \ge 0 \\ (a_4 \times k, a_3 \times k, a_2 \times k, a_1 \times k) & if \quad k < 0 \end{cases} \quad (7)$$

Division:

$$\tilde{A} \oslash \tilde{B} = (a_1/b_4, a_2/b_3, a_3/b_2, a_4/b_1) \quad (8)$$

$$\tilde{A} / k = \begin{cases} (a_1/k, a_2/k, a_3/k, a_4/k) & if \quad k \ge 0 \\ (a_4/k, a_3/k, a_2/k, a_1/k) & if \quad k < 0 \end{cases} \quad (9)$$

Let $\tilde{A} = (a_1, a_2, a_3, a_4)$ is a TFN. Then, the defuzzified (crisp) value of this fuzzy number can be calculated by using Eq. (10) (Keshavarz Ghorabaee et al. 2014)

$$k(\tilde{A}) = \frac{1}{3}(a_1 + a_2 + a_3 + a_4) - \frac{a_3 x a_4 - a_1 x a_2}{(a_3 + a_4) - (a_1 + a_2)} \quad (10)$$

Let $\tilde{A} = (a_1, a_2, a_3, a_4)$ is a TFN. Psi(ψ) function, which aims to find the maximum between a TFN and zero, is expressed in Eq. (11).

$$\psi(\tilde{A}) = \begin{cases} \tilde{A} & if \quad k(\tilde{A}) > 0 \\ \tilde{0} & if \quad k(\tilde{A}) \le 0 \end{cases} \quad (11)$$

where $\tilde{0} = (0, 0, 0, 0)$.

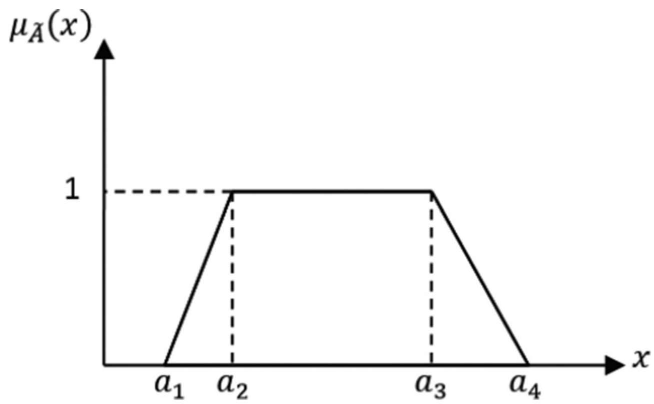

Figure 1. A Trapezoidal fuzzy number (TFN).

Fuzzy EDAS method

The EDAS method was first introduced by Keshavarz Ghorabaee et al. (2015). The method was mainly based on the idea of evaluating the alternatives using two distance measures, namely the distance from the Positive Distance from Average (PDA) and the Negative Distance from Average (NDA). The fuzzy extension of this method was developed by Keshavarz Ghorabaee et al. (2016). The fuzzy EDAS method enables decision-makers to express the weights of the criteria and evaluate the alternatives according to the criteria using linguistic terms, which are quantified by positive TFNs. Assume that there are a set of n alternatives ($A = \{A_1, A_2, \ldots, A_n\}$), a set of m criteria ($C = \{c_1, c_2, \ldots c_m\}$) and K decision-makers ($D = \{D_1, D_2, \ldots D_K\}$). The steps of the fuzzy EDAS method can be summarized as follows (Keshavarz Ghorabaee et al. 2016; Stević et al. 2018):

Step 1: Consult decision makers, identify the evaluation criteria and alternatives, determine the linguistic terms that will be used for assigning criteria weights and evaluating the alternatives, and construct the matrix of criteria weights, displayed as follows:

$$W = [\tilde{w}_j]_{1\times m} \tag{12}$$

$$\tilde{w}_j = \frac{1}{K}\sum_{p=1}^{K}\tilde{w}_j^p \tag{13}$$

where $\tilde{w}_j^p$ represents the weight of criterion $c_j (1 \le j \le m)$ determined by the p^{th} decision-maker $(1 \le p \le K)$.

Step 2: Consult decision makers and establish the average fuzzy decision matrix, in which the alternatives are evaluated with respect to the evaluation criteria using the appropriate linguistic scale, shown as follows:

$$X = [\tilde{x}_{ij}]_{n\times m} \tag{14}$$

$$\tilde{x}_{ij} = \frac{1}{K}\sum_{p=1}^{K}\tilde{x}_{ij}^p \tag{15}$$

where $\tilde{x}_{ij}^p$ represents the performance value of alternative $A_i (1 \le i \le n)$ with respect to the criterion $c_j (1 \le j \le m)$ assigned by the p^{th} decision-maker $(1 \le p \le K)$.

Step 3: Construct the fuzzy matrix of average solutions, displayed as follows:

$$AV = [\tilde{av}_j]_{1\times m} \tag{16}$$

$$\tilde{av}_j = \frac{1}{n}\sum_{i=1}^{n}\tilde{x}_{ij} \tag{17}$$

The elements of this matrix $\tilde{av}_j$ signify the average solutions with respect to each criterion.

Step 4: Let B is the set of beneficial criteria and$N$ is the set of non-beneficial criteria. The matrices of positive (PDA) and negative distance from average solutions(NDA) are computed depending on the type of criteria, namely beneficial or non-beneficial, as given:

$$PDA = [\tilde{pda}_{ij}]_{n\times m} \tag{18}$$

$$NDA = [\tilde{nda}_{ij}]_{n\times m} \tag{19}$$

$$\tilde{pda}_{ij} = \begin{cases} \dfrac{\psi(\tilde{x}_{ij}\theta\tilde{av}_j)}{k(\tilde{av}_j)} & if \quad j \in B \\ \dfrac{\psi(\tilde{av}_j\theta\tilde{x}_{ij})}{k(\tilde{av}_j)} & if \quad j \in N \end{cases} \tag{20}$$

$$\tilde{nda}_{ij} = \begin{cases} \dfrac{\psi(\tilde{av}_j\theta\tilde{x}_{ij})}{k(\tilde{av}_j)} & if \quad j \in B \\ \dfrac{\psi(\tilde{x}_{ij}\theta\tilde{av}_j)}{k(\tilde{av}_j)} & if \quad j \in N \end{cases} \tag{21}$$

where $\tilde{pda}_{ij}$ and $\tilde{nda}_{ij}$ denote for the positive and negative distance of performance value of i^{th} alternative from the average solution with respect to j^{th} criterion, respectively.

Step 5: Compute the weighted sum of positive and negative distances for all alternatives, displayed as follows:

$$\tilde{sp}_i = \sum_{j=1}^{m}(\tilde{w}_j \otimes \tilde{pda}_{ij}) \tag{22}$$

$$\tilde{sn}_i = \sum_{j=1}^{m}(\tilde{w}_j \otimes \tilde{nda}_{ij}) \tag{23}$$

Step 6: Calculate the normalized values of $\tilde{sp}_i$ and $\tilde{sn}_i$ for all alternatives as shown:

$$\tilde{nsp}_i = \frac{\tilde{sp}_i}{\max_i(k(\tilde{sp}_i))} \tag{24}$$

$$\tilde{nsn}_i = 1 - \frac{\tilde{sn}_i}{\max_i(k(\tilde{sn}_i))} \tag{25}$$

Step 7: The appraisal score $\tilde{as}_i$ for all alternatives is computed as follows:

$$\tilde{as}_i = \frac{1}{2}(\tilde{nsp}_i \oplus \tilde{nsn}_i) \tag{26}$$

Step 8: Rank the alternatives with respect to the decreasing values of appraisal scores $\tilde{as}_i$, since the alternative with the highest appraisal score is the best alternative.

In this study, the fuzzy EDAS method was applied for solving the HVAC-AHU system and its supplier selection problem in a green multifunctional shopping center project located in Moscow. In order to solve the supplier selection problem for the studied project, first the decision making team, whose members were civil engineers working in the purchasing department of the construction company in question and were responsible for evaluating and/or selecting suppliers for the case study, was formed. Secondly, the decision making team determined the supplier selection criteria that would be taken into account during the supplier evaluation/selection process and alternative HVAC-AHU system suppliers. Thirdly, the decision-makers decided on the linguistic terms that they would use for assigning criteria weights and evaluating alternatives. Fourthly, the decision making team assigned weights to the criteria they determined and evaluated the alternatives with respect to these criteria using the linguistic terms. Finally, the fuzzy EDAS computations were performed; the alternatives were ranked with respect to the

Table 1. Linguistic terms and their corresponding TFN (Keshavarz Ghorabaee et al. 2016).

Terms	TFN for weighting criteria	TFN for rating alternatives
Very Low (VL)	(0, 0, 0.1, 0.2)	(0, 0, 1, 2)
Low (L)	(0.1, 0.2, 0.2, 0.3)	(1, 2, 2, 3)
Medium Low (ML)	(0.2, 0.3, 0.4, 0.5)	(2, 3, 4, 5)
Medium (M)	(0.4, 0.5, 0.5, 0.6)	(4, 5, 5, 6)
Medium High (MH)	(0.5, 0.6, 0.7, 0.8)	(5, 6, 7, 8)
High (H)	(0.7, 0.8, 0.8, 0.9)	(7, 8, 8, 9)
Very High (VH)	(0.8, 0.9, 1, 1)	(8, 9, 10, 10)

calculated appraisal scores, and the alternative HVAC-AHU system supplier with the highest appraisal score was selected.

Case study of HVAC-AHU supplier selection with environmental considerations

The case study is related to the selection of the most appropriate HVAC-AHU system and its supplier for a green multifunctional shopping center project located on Moscow's Yartsevskaya Street, which is a part of a prestigious neighborhood that features universities, public buildings, medical facilities, and residential amenities. The entire complex consists of 200 stores, 2,000 parking lots, a two level hypermarket, a sport facility and swimming pool, movie theatre with eight salons, an entertainment center, a two-level sky bar with terraces, food court areas and restaurants, 25,000 m^2 office volumes and several residential apartment units. The total construction area is 245,000 m^2 and the gross leasable area of retail space is 61,000 m^2. It is one of the first multifunctional buildings in the Russian commercial real estate market.

The studied multifunctional shopping center project was awarded for The Cityscape Award for Emerging Markets by Cityscape Global Project, Best Shopping Center Award given by the Russian Council of Shopping Centers (RCSC), and The Best Facility for Customers Award, Silver Mark by The Review Competition. This case study is selected as it is a complex and prestigious project. Moreover, the construction was undertaken by a large-scale Turkish contractor, which mainly operates in international construction markets, and it was awarded for 'Green Standards - Gold' certification level with the credit achievement ratio of 61.32%.

Selecting proper HVAC components plays a critical role in obtaining this level of certification and as the building does not use any renewable energy sources. In the studied project, HVAC-AHUs constituted over 1/3 of the equipment cost, which accounts for approximately USD 2.5 million. The purchasing department of this company was in charge of procuring the HVAC-AHU systems. Five civil engineers working in this department determined six alternative HVAC-AHU systems and their suppliers and a total of eight criteria, which are: price of product (C1), warranty period (C2), delivery lead time (C3), conformity with the specifications (C4), quality of communication with the supplier (C5), quality of maintenance and spare parts service (C6), conformity with Energy Performance of Buildings Directives for Green Production, Design and Supply (C7), and efficiency level of motors (C8). While price of product (C1) and delivery lead time (C3) are non-beneficial criteria, the remaining six criteria are beneficial criteria.

Having determined the evaluation criteria and the alternatives, five decision-makers decided on the linguistic terms that they will use for assigning criteria weights and evaluating alternatives. The linguistic terms and their corresponding TFN are presented in Table 1.

Table 2. The weights of the criteria assigned by the decision makers expressed in linguistic terms.

	Criteria							
Decision Maker #	C1	C2	C3	C4	C5	C6	C7	C8
DM1	VH	MH	VH	VH	MH	MH	H	H
DM2	H	H	MH	VH	MH	VH	VH	H
DM3	VH	H	MH	VH	MH	H	H	VH
DM4	M	H	M	VH	M	H	H	MH
DM5	VH	H	MH	VH	MH	H	H	VH

Table 3. Five decision-makers' evaluations of the alternatives with respect to the criteria expressed in linguistic terms.

		Criteria							
Decision Maker #	Alternative HVAC-AHUs	C1	C2	C3	C4	C5	C6	C7	C8
DM1	A1	L	MH	ML	VH	VH	H	H	H
	A2	L	H	VL	H	H	MH	M	MH
	A3	ML	H	L	VH	VH	H	H	H
	A4	M	M	VL	M	MH	ML	M	M
	A5	L	H	MH	M	H	ML	MH	MH
	A6	ML	VH	MH	H	H	H	MH	MH
DM2	A1	L	H	ML	H	VH	M	H	H
	A2	L	VH	VL	H	H	H	MH	VH
	A3	ML	H	L	H	H	M	MH	H
	A4	M	ML	L	ML	MH	L	M	MH
	A5	M	H	ML	M	M	MH	MH	M
	A6	ML	VH	ML	ML	M	H	ML	ML
DM3	A1	MH	MH	ML	VH	VH	M	MH	VH
	A2	L	H	L	MH	M	H	M	VH
	A3	M	MH	L	H	H	H	H	H
	A4	VL	ML	VL	MH	MH	M	ML	MH
	A5	M	L	VH	H	H	ML	H	H
	A6	M	VH	VH	H	VH	H	M	H
DM4	A1	M	H	ML	H	VH	H	H	H
	A2	L	VH	L	MH	MH	VH	H	VH
	A3	L	H	L	H	H	MH	MH	H
	A4	VL	ML	L	ML	MH	L	M	M
	A5	M	H	ML	M	M	MH	H	MH
	A6	L	VH	ML	ML	M	H	MH	M
DM5	A1	MH	H	L	H	VH	H	VH	H
	A2	ML	MH	ML	MH	MH	MH	MH	VH
	A3	MH	H	L	H	H	MH	VH	H
	A4	ML	ML	VL	M	MH	M	H	MH
	A5	M	ML	H	H	H	VH	VH	MH
	A6	MH	VH	MH	M	VH	H	H	H

The decision-makers assigned weights to eight criteria. The matrix of criteria weights is presented in Table 2.

Having assigned the criteria weights, five decision makers evaluated the alternatives with respect to eight criteria. The matrix of alternative evaluations is presented in Table 3.

The average weighting matrix of the criteria constructed using Eqs. (12) and (13), their corresponding crisp values, and the normalized crisp values are presented in Table 4. As it can be seen in the last column of Table 4, three criteria, namely conformity with the specifications (C4), conformity with Energy Performance of Buildings Directives for Green Production, Design and Supply (C7), efficiency level of motors (C8), are very important for the studied project. This finding is very reasonable as the studied project was awarded 'Green Standards - Gold' certification level and the conformity with the specifications related to the HVAC-AHU systems, conformity with Energy Performance of Buildings Directives for Green Production, Design and Supply, and efficiency level of motors, play a critical role in achieving credits from the energy saving and energy efficiency section. These three criteria were followed by the price of product (C1) and quality of maintenance and spare parts service (C6) criteria.

Table 4. The average weighting matrix.

Criteria	W_j	$k(W_j)$	$nk(W_j)$
C1	(0.70, 0.80, 0.86, 0.90)	0.812	0.130
C2	(0.66, 0.76, 0.78, 0.88)	0.770	0.124
C3	(0.54, 0.64, 0.72, 0.80)	0.674	0.108
C4	(0.80, 0.90, 1.00, 1.00)	0.922	0.148
C5	(0.48, 0.58, 0.66, 0.76)	0.620	0.099
C6	(0.68, 0.78, 0.82, 0.90)	0.794	0.127
C7	(0.72, 0.82, 0.84, 0.92)	0.824	0.132
C8	(0.70, 0.80, 0.86, 0.92)	0.818	0.131

Table 5. The elements of average decision matrix and the average solution matrix.

Criteria	A1				A2				A3			
C1	3.20	4.20	4.60	5.60	1.20	2.20	2.40	3.40	2.80	3.80	4.40	5.40
C2	6.20	7.20	7.60	8.60	7.00	8.00	8.60	9.20	6.60	7.60	7.80	8.80
C3	1.80	2.80	3.60	4.60	0.80	1.40	2.00	3.00	1.00	2.00	2.00	3.00
C4	7.40	8.40	8.80	9.40	5.80	6.80	7.40	8.40	7.20	8.20	8.40	9.20
C5	8.00	9.00	10.00	10.00	5.60	6.60	7.00	8.00	7.20	8.20	8.40	9.20
C6	5.80	6.80	6.80	7.80	6.40	7.40	8.00	8.80	5.60	6.60	7.00	8.00
C7	6.80	7.80	8.20	9.00	5.00	6.00	6.40	7.40	6.40	7.40	8.00	8.80
C8	7.20	8.20	8.40	9.20	7.40	8.40	9.40	9.60	7.00	8.00	8.00	9.00
Criteria	A4				A5				A6			
C1	2.00	2.60	3.20	4.20	3.40	4.40	4.40	5.40	2.80	3.80	4.40	5.40
C2	2.40	3.40	4.20	5.20	4.80	5.80	6.00	7.00	8.00	9.00	10.00	10.00
C3	0.40	0.80	1.40	2.40	4.80	5.80	6.60	7.40	4.40	5.40	6.40	7.20
C4	3.40	4.40	5.00	6.00	5.20	6.20	6.20	7.20	4.40	5.40	5.80	6.80
C5	5.00	6.00	7.00	8.00	5.80	6.80	6.80	7.80	6.20	7.20	7.60	8.20
C6	2.40	3.40	3.60	4.60	4.40	5.40	6.40	7.20	7.00	8.00	8.00	9.00
C7	4.20	5.20	5.40	6.40	6.40	7.40	8.00	8.80	4.60	5.60	6.20	7.20
C8	4.60	5.60	6.20	7.20	5.20	6.20	6.80	7.80	5.00	6.00	6.40	7.40
Criteria	AV											
C1	2.57	3.50	3.90	4.90								
C2	5.83	6.83	7.37	8.13								
C3	2.20	3.03	3.67	4.60								
C4	5.57	6.57	6.93	7.83								
C5	6.30	7.30	7.80	8.53								
C6	5.27	6.27	6.63	7.57								
C7	5.57	6.57	7.03	7.93								
C8	6.07	7.07	7.53	8.37								

Table 6. The values of PDA.

Criteria	A1				A2				A3			
C1	0.00	0.00	0.00	0.00	−0.22	0.30	0.46	0.99	0.00	0.00	0.00	0.00
C2	−0.28	−0.02	0.11	0.39	−0.16	0.09	0.25	0.48	−0.22	0.03	0.14	0.42
C3	−0.71	−0.17	0.26	0.83	−0.24	0.31	0.67	1.12	−0.24	0.31	0.49	1.07
C4	−0.06	0.22	0.33	0.57	−0.30	−0.02	0.12	0.42	−0.09	0.19	0.27	0.54
C5	−0.07	0.16	0.36	0.50	0.00	0.00	0.00	0.00	−0.18	0.05	0.15	0.39
C6	−0.27	0.03	0.08	0.39	−0.18	0.12	0.27	0.55	−0.31	−0.01	0.11	0.43
C7	−0.17	0.11	0.24	0.51	0.00	0.00	0.00	0.00	−0.23	0.05	0.21	0.48
C8	−0.16	0.09	0.18	0.43	−0.13	0.12	0.32	0.49	−0.19	0.06	0.13	0.40
Criteria	A4				A5				A6			
C1	−0.44	0.08	0.35	0.78	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	−0.02	0.23	0.45	0.59
C3	−0.06	0.48	0.85	1.24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	−0.09	0.21	0.27	0.58
C7	0.00	0.00	0.00	0.00	−0.23	0.05	0.21	0.48	0.00	0.00	0.00	0.00
C8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 7. The values of NDA.

Criteria	A1				A2				A3			
C1	−0.46	0.08	0.30	0.82	0.00	0.00	0.00	0.00	−0.56	−0.03	0.24	0.76
C2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C5	0.00	0.00	0.00	0.00	−0.23	0.04	0.16	0.39	0.00	0.00	0.00	0.00
C6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C7	0.00	0.00	0.00	0.00	−0.27	0.02	0.15	0.43	0.00	0.00	0.00	0.00
C8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Criteria	A4				A5				A6			
C1	0.00	0.00	0.00	0.00	−0.40	0.13	0.24	0.76	−0.56	−0.03	0.24	0.76
C2	0.09	0.37	0.56	0.82	−0.17	0.12	0.22	0.47	0.00	0.00	0.00	0.00
C3	0.00	0.00	0.00	0.00	0.06	0.63	1.06	1.54	−0.06	0.51	1.00	1.48
C4	−0.06	0.23	0.38	0.66	−0.24	0.05	0.11	0.39	−0.18	0.11	0.23	0.51
C5	−0.23	0.04	0.24	0.47	−0.20	0.07	0.13	0.37	−0.25	−0.04	0.08	0.31
C6	0.10	0.41	0.50	0.80	−0.30	−0.02	0.19	0.49	0.00	0.00	0.00	0.00
C7	−0.12	0.17	0.27	0.55	0.00	0.00	0.00	0.00	−0.24	0.05	0.21	0.49
C8	−0.16	0.12	0.27	0.52	−0.24	0.04	0.18	0.44	−0.18	0.09	0.21	0.46

The elements of average decision matrix and the average solution matrix constructed using Eqs. (14)–(17) is presented in Table 5.

Having calculated the elements of average decision matrix and the average solution matrix, positive distances (PDA) and negative distances (NDA) from the average solutions depending on the type of criterion (i.e., beneficial or non-beneficial) are computed using Eqs. (18)–(21). The values of PDA are presented in Table 6 and the values of NDA are displayed in Table 7.

After computing the PDA and NDA values, the weighted sum of positive and negative distances for all alternatives, their normalized values, the appraisal scores of all alternatives, and their corresponding crisp values are calculated using Eqs. (22)–(26). The findings are displayed in Table 8.

As it can be seen in the last column of Table 7, A2 has the highest appraisal score, which indicates that it is the most appropriate alternative, and A5 has the lowest appraisal score, which means that it is the worst alternative.

Sensitivity analysis and discussion

After calculating the appraisal scores and thereby determining the ranking of the alternatives, it is necessary to show the stability of the model and the sensitivity of the findings to any change in the weights of particular criteria. Therefore, a sensitivity analysis was performed. The steps previously employed by Keshavarz Ghorabaee et al. (2016) and Stević et al. (2019) were followed when carrying out the sensitivity analysis in this study.

The sensitivity analysis was performed in three main steps. In the first step of the sensitivity analysis, eight sets of criteria weights were generated (see Figure 2). As it can be seen in Figure 2, in each set, while one criterion has the highest weight and one criterion has the lowest weight, the others have a weight between them. In the first set, C1 has the lowest weight (i.e., 2.8%) and C8 has the highest weight (i.e., 22.2%) in order to satisfy the condition that the sum of the weights of eight criteria equals to one. In this set, the weights of the remaining criteria are as follows: C2 5.6%, C3 8.3%, C4 11.1%, C5 13.9%, C6 16.7%, and C7 19.4. Similarly in the second set, C8 has the lowest weight (i.e., 2.8%) and C7 has the highest weight (i.e., 22.2%).

The appraisal scores that each alternative supplier attains depending on the criteria weights assigned in different sets are presented in Figure 3.

Based on the judgements of five decision makers, conformity with the specifications (C4) (0.148), conformity with Energy Performance of Buildings Directives for Green Production, Design and Supply (C7) (0.132), efficiency level of motors (C8) (0.131), and price of product (C1) (0.130) have the highest weights (see the last column of Table 4). When the weight of the fourth criterion decreases (i.e., Sets 6, 7, and 8), suppler alternatives A2, A3 and A1 have very high appraisal scores (see Figure 3). Out of three sets in which the weights of the seventh and eighth criteria decrease (i.e., Sets 3, 4, 5, and 8), A3 ranks first and A2 ranks second in only Set 4. However, their appraisal

Table 8. The weighted sum of distances, their normalized values, the appraisal scores, and the crisp values.

Alternatives	$\tilde{sp}_i$	$\tilde{sn}_i$	$\tilde{nsp}_i$
A1	(−1.48, 0.34, 1.27, 3.17)	(−0.41, 0.06, 0.25, 0.73)	(−1.22, 0.28, 1.05, 2.62)
A2	(−1.12, 0.67, 1.69, 3.58)	(−0.42, 0.04, 0.23, 0.70)	(−0.93, 0.55, 1.40, 2.96)
A3	(−1.27, 0.51, 1.21, 3.25)	(−0.51, −0.02, 0.21, 0.69)	(−1.05, 0.42, 1.00, 2.69)
A4	(−0.44, 0.37, 0.91, 1.70)	(−0.36, 1.08, 1.85, 3.45)	(−0.37, 0.31, 0.75, 1.40)
A5	(−0.21, 0.04, 0.18, 0.44)	(−1.36, 0.70, 1.65, 3.85)	(−0.17, 0.04, 0.15, 0.36)
A6	(−0.10, 0.34, 0.57, 1.04)	(−1.32, 0.50, 1.57, 3.50)	(−0.08, 0.28, 0.47, 0.86)
Alternatives	$\tilde{nsn}_i$	$\tilde{as}_i$	$k(\tilde{as}_i)$
A1	(0.51, 0.83, 0.96, 1.27)	(−0.35, 0.56, 1.00, 1.95)	0.79
A2	(0.54, 0.84, 0.97, 1.28)	(−0.19, 0.70, 1.19, 2.12)	**0.95**
A3	(0.55, 0.86, 1.02, 1.34)	(−0.25, 0.64, 1.01, 2.01)	0.86
A4	(−1.28, −0.22, 0.29, 1.24)	(−0.82, 0.04, 0.52, 1.32)	0.26
A5	(−1.55, −0.10, 0.54, 1.90)	(−0.86, −0.03, 0.34, 1.13)	0.14
A6	(−1.32, −0.04, 0.67, 1.88)	(−0.70, 0.12, 0.57, 1.37)	0.34

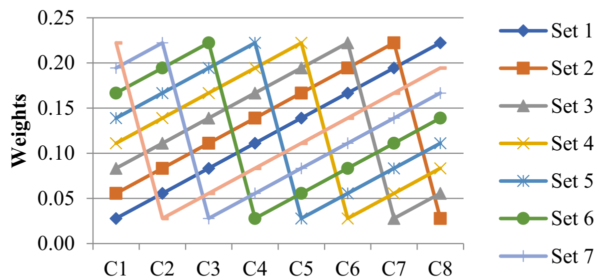

Figure 2. The simulated weights for sensitivity analysis.

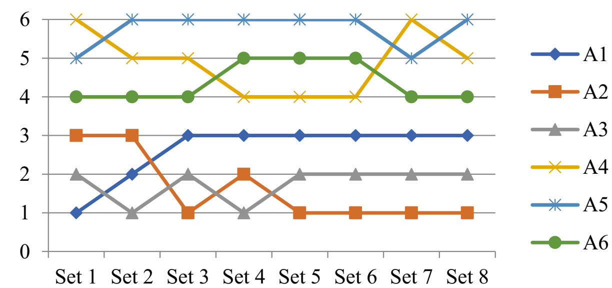

Figure 4. The rank of alternatives in different sets.

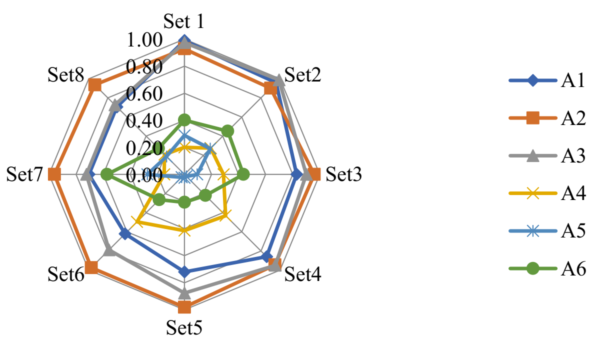

Figure 3. Results of sensitivity analysis.

scores are very close, namely 0.950 for A3 and 0.945 for A2. When the weight of the first criterion is very low in Sets 1 and 2, A1 and A3 have the highest scores, and A2 has the third highest score. Nonetheless, their appraisal scores are very close to each other.

Figure 4 shows the ranking of each alternative in each set of criteria weights.

As it can be seen in Figure 4, the ranks of alternatives change in different sets depending on the weights of the criteria. While A2 is the best alternative in 5 of 8 sets, A3 is the best alternative in 2 sets, namely Set 2 and Set 4. On the other hand, A5 is the worst alternative in 6 out of 8 sets. It can be concluded that A2 is the best alternative based on the findings of the sensitivity analysis. In the studied project, the decision-makers approved A2, decided to procure this HVAC-AHU system, and they did not experience any serious problems during the supply and certification processes.

Conclusion and recommendations

Buildings are responsible for the energy consumption and greenhouse gas emission. Since commercial buildings consume the highest energy when compared to the other types of buildings, this type of buildings plays a critical role in achieving sustainable development. HVAC systems, but especially AHUs consume a major portion of the energy delivered to the commercial buildings. In the traditional supplier selection approach, cost was the most important criterion. However, environmental aspects have recently become central to the supplier selection decision. Therefore, selecting the most appropriate HVAC-AHU system and its supplier is crucial for improving the energy efficiency of air-conditioned commercial buildings and obtaining a good score from the green certification system according to which the project in question is evaluated. Selecting the proper HVAC-AHU system and its supplier from a set of possible alternatives is not an easy task for contractors as this decision is influenced by several compromising and conflicting criteria. Besides, this decision is usually made by multiple decision makers, who may have different viewpoints and prefer to express their evaluations by linguistic terms.

This study employs fuzzy EDAS method for selecting the most appropriate HVAC-AHU system and its supplier for a green multifunctional shopping center project located in Moscow. The employed method enables decision makers to specify their preferences by linguistic terms using TFNs and allows for aggregating subjective judgements of different decision makers in order to come to a final decision. One of the superiority of fuzzy EDAS is that it allows for both calculating the criteria weights and ranking the alternatives in a simple and easy way. In the studied project, the decision makers decided to select the HVAC-AHU system and its supplier ranked first (i.e., A2) and stated that they had not encountered any severe problems during the supply and certification processes. A sensitivity analysis was also performed to show the validity and stability of the ranking results when the criteria weights are changed. The results of sensitivity analysis show that the proposed method is stable in different criteria weights and A2 is the best alternative. The decision makers found fuzzy EDAS method very convenient and stated that they could employ it in future supplier selection problems. One of the future directions of this research is that different fuzzy MCGDM based on fuzzy type 2 sets methods can be employed to solve the same problem and the results can be compared with the findings of this study.

Disclosure statement

No potential conflict of interest was reported by the author(s).

References

Akcay EC, Arditi D. 2017. Desired points at minimum cost in the “optimize energy performance” credit of leed certification. J Civil Eng Manage. 23(6):796–805.

Aktacir MA, Büyükalaca O, Yılmaz T. 2010. A case study for influence of building thermal insulation on cooling load and air-conditioning system in the hot and humid regions. Appl Energy. 87(2):599–607.

Amindoust A, Ahmed S, Saghafinia A, Bahreininejad A. 2012. Sustainable supplier selection: A ranking model based on fuzzy inference system. Appl Soft Comput. 12(6):1668–1677.

Ampratwum G, Agyekum K, Adinyira E, Duah D. 2019. A framework for the implementation of green certification of buildings in Ghana. Int J Constr Manage. 1–15. doi:10.1080/15623599.2019.1613207

Aretoulis GN, Kalfakakou GP, Striagka FZ. 2010. Construction material supplier selection under multiple criteria. Oper Res Int J. 10(2):209–230.

Arroyo P, Tommelein ID, Ballard G, Rumsey P. 2016. Choosing by advantages: A case study for selecting an HVAC system for a net zero energy museum. Energy Build. 111:26–36.

Ascione F, Bianco N, De Stasio C, Mauro GM, Vanoli GP. 2017. A new comprehensive approach for cost-optimal building design integrated with the multi-objective model predictive control of HVAC systems. Sustain Cities Soc. 31:136–150.

Avgelis A, Papadopoulos AM. 2009. Application of multicriteria analysis in designing HVAC systems. Energy Build. 41(7):774–780.

Azar E, Menassa CC. 2012. A comprehensive analysis of the impact of occupancy parameters in energy simulation of office buildings. Energy Build. 55:841–853.

Baniassadi A, Heusinger J, Sailor DJ. 2018. Building energy savings potential of a hybrid roofing system involving high albedo, moisture retaining foam materials. Energy Build. 169:283–294.

Bichiou Y, Krarti M. 2011. Optimization of envelope and HVAC systems selection for residential buildings. Energy Build. 43(12):3373–3382.

BRE 2019. BREAAM projects listed for the Moscow city; [accessed 2019 December 26]. https://tools.breeam.com/projects/explore/map.jsp?sectionid=0&projectType=&rating=&certNo=&buildingName=&client=&developer=&certBody=&assessor=&addressPostcode=&countryId=&partid=10023&Submit=Search.

Carreira P, Costa AA, Mansu V, Arsénio A. 2018. Can HVAC really learn from users? A simulation-based study on the effectiveness of voting for comfort and energy use optimisation. Sustain Cities Soc. 41:275–285.

Chinese D, Nardin G, Saro O. 2011. Multi-criteria analysis for the selection of space heating systems in an industrial building. Energy. 36(1):556–565.

Dixit V, Chaudhuri A, Srivastava RK. 2018. Procurement scheduling in engineer procure construct projects: a comparison of three fuzzy modelling approaches. Int J Constr Manage. 18(3):189–206.

Doan DT, Ghaffarianhoseini A, Naismith N, Zhang T, Ghaffarianhoseini A, Tookey J. 2017. A critical comparison of green building rating systems. Build Environ. 123:243–260.

Durdyev S, Zavadskas EK, Thurnell D, Banaitis A, Ihtiyar A. 2018. Sustainable Construction Industry in Cambodia: Awareness, Drivers and Barriers. Sustainability. 10(2):392.

Dwaikat LN, Ali KN. 2016. Green buildings cost premium: A review of empirical evidence. Energy Build. 110:396–403.

Ebadi MJ, Suleiman M, Ismail FB, Ahmadian A, Shahryari MR, Salahshour S. 2013. A new distance measure for trapezoidal fuzzy numbers. Math Prob Eng. 2013:1–4.

Ecer F. 2018. Third-party logistics (3PLs) provider selection via Fuzzy AHP and EDAS integrated model. Technol Econ Develop Econ. 24(2):615–634.

El-Sayegh SM, Basamji M, Haj Ahmad A, Zarif N. 2019. Key contractor selection criteria for green construction projects in the UAE. Int J Constr Manage. 1–11. doi:10.1080/15623599.2019.1610545

Fasiuddin M, Budaiwi I, Abdou A. 2010. Zero-investment HVAC system operation strategies for energy conservation and thermal comfort in commercial buildings in hot-humid climate. Int J Energy Res. 34(1):1–19.

Garnier A, Eynard J, Caussanel M, Grieu S. 2015. Predictive control of multizone heating, ventilation and air-conditioning systems in non-residential buildings. Appl Soft Comput. 37:847–862.

Ghahramani A, Karvigh SA, Becerik-Gerber B. 2017. HVAC system energy optimization using an adaptive hybrid metaheuristic. Energy Build. 152: 149–161.

Ghodrati N, Samari M, Shafiei MWM. 2012. Green buildings impacts on occupants’ health and productivity. J Appl Sci Res. 8(8):4235–4241.

Goudarzi H, Mostafaeipour A. 2017. Energy saving evaluation of passive systems for residential buildings in hot and dry regions. Renew Sustain Energy Rev. 68:432–446.

Gul MS, Patidar S. 2015. Understanding the energy consumption and occupancy of a multi-purpose academic building. Energy Build. 87:155–165.

Ho W, Xu X, Dey PK. 2010. Multi-criteria decision making approaches for supplier evaluation and selection: A literature review. Eur J Oper Res. 202(1):16–24.

Huang P, Huang G, Wang Y. 2015. HVAC system design under peak load prediction uncertainty using multiple-criterion decision making technique. Energy Build. 91:26–36.

Juodagalvienė B, Turskis Z, Šaparauskas J, Endriukaitytė A. 2017. Integrated multi-criteria evaluation of house’s plan shape based on the EDAS and SWARA methods. Eng Struct Technol. 9(3):117–125.

Kahraman C, Cebi S, Tuysuz F. 2010. Fuzzy location selection techniques. In: Cengiz Kahraman and Mesut Yavuz, editors. Production engineering and management under fuzziness. Berlin: Springer; p. 329–358.

Kahraman C, Keshavarz Ghorabaee M, Zavadskas EK, Cevik Onar S, Yazdani M, Oztaysi B. 2017. Intuitionistic fuzzy EDAS method: an application to solid waste disposal site selection. J Environ Eng Landscape Manage. 25(1):1–12.

Keshavarz Ghorabaee M, Amiri M, Sadaghiani JS, Goodarzi GH. 2014. Multiple criteria group decision-making for supplier selection based on COPRAS method with interval type-2 fuzzy sets. Int J Adv Manuf Technol. 75(5-8):1115–1130.

Keshavarz Ghorabaee M, Amiri M, Zavadskas EK, Antucheviciene J. 2018. A new hybrid fuzzy MCDM approach for evaluation of construction equipment with sustainability considerations. Arch Civil Mech Eng. 18(1):32–49.

Keshavarz Ghorabaee M, Amiri M, Zavadskas EK, Turskis Z, Antucheviciene J. 2017a. A new multi-criteria model based on interval type-2 fuzzy sets and EDAS method for supplier evaluation and order allocation with environmental considerations. Comput Ind Eng. 112:156–174.

Keshavarz Ghorabaee M, Amiri M, Zavadskas EK, Turskis Z, Antucheviciene J. 2017b. Stochastic EDAS method for multi-criteria decision-making with normally distributed data. IFS. 33(3):1627–1638.

Keshavarz Ghorabaee M, Zavadskas EK, Amiri M, Turskis Z. 2016. Extended EDAS method for fuzzy multi-criteria decision-making: an application to supplier selection. Int J Comput Commun. 11(3):358–371.

Keshavarz Ghorabaee M, Zavadskas EK, Olfat L, Turskis Z. 2015. Multi-criteria inventory classification using a new method of evaluation based on distance from average solution (EDAS). Informatica. 26(3):435–451.

Kim YJ, Ahn KU, Park CS. 2014. Decision making of HVAC system using Bayesian Markov chain Monte Carlo method. Energy Build. 72:112–121.

Kondrachuk OE, Petrenko YI. 2015. Prospects of development of ecological and energy efficiency building in Russia. Fund Res. 11:579–583.

Kusiak A, Li M. 2010. Cooling output optimization of an air handling unit. Appl Energy. 87(3):901–909.

Kusiak A, Li M, Tang F. 2010. Modeling and optimization of HVAC energy consumption. Appl Energy. 87(10):3092–3102.

Luzon B, El-Sayegh SM. 2016. Evaluating supplier selection criteria for oil and gas projects in the UAE using AHP and Delphi. Int J Constr Manage. 16(2):175–183.

Plebankiewicz E, Kubek D. 2016. Multicriteria selection of the building material supplier using AHP and fuzzy AHP. J Constr Eng Manage. 142(1):04015057. 04015057.

Porfiriev BN, Dmitriev A, Vladimirova I, Tsygankova A. 2017. Sustainable development planning and green construction for building resilient cities: Russian experiences within the international context. Environ Hazards. 16(2):165–179.

Rao C, Goh M, Zheng J. 2017. Decision mechanism for supplier selection under sustainability. Int J Info Tech Dec Mak. 16(01):87–115.

Roghanian E, Alipour M, Rezaei M. 2018. An improved fuzzy critical chain approach in order to face uncertainty in project scheduling. Int J Constr Manage. 18(1):1–13.

Sirazetdinov R, Mavliutova A, Zagidullina G. 2018. Environmental standardization of residential real estate according to “Green standards. In MATEC Web Conf . (193 :03001. EDP Sciences.

Stević Ž, Vasiljević M, Puška A, Tanackov I, Junevičius R, Vesković S. 2019. Evaluation of suppliers under uncertainty: a multiphase approach based on fuzzy AHP and fuzzy EDAS. Transport. 34(1):52–66.

Stević Ž, Vasiljević M, Zavadskas EK, Sremac S, Turskis Z. 2018. Selection of carpenter manufacturer using fuzzy EDAS method. EE. 29(3):281–290.

Széll M. 2003. Intelligent buildings, integrating design. Period Polytech Civil Eng. 47(1):49–56.

Trinkūnienė E, Podvezko V, Zavadskas EK, Jokšienė I, Vinogradova I, Trinkūnas V. 2017. Evaluation of quality assurance in contractor contracts by multi-attribute decision-making methods. Econ Res–Ekonomska Istraživanja. 30(1):1152–1180.

Turskis Z, Juodagalvienė B. 2016. A novel hybrid multi-criteria decision-making model to assess a stairs shape for dwelling houses. J Civil Eng Manage. 22(8):1078–1087.

Turskis Z, Morkunaite Z, Kutut V. 2017. A hybrid multiple criteria evaluation method of ranking of cultural heritage structures for renovation projects. Int J Strateg Property Manage. 21(3):318–329.

USGBC 2019. LEED projects listed for the Moscow city; [accessed 2019 December 26] https://www.usgbc.org/projects?match=all&smartf=%28LOWER%28node_data_field_city_name.field_city_name_value%29%20like%20%27%25%25moscow%25%27%29&smartfiltername=&smartfid=.

Wong BK, Lai VS. 2011. A survey of the application of fuzzy set theory in production and operations management: 1998–2009. Int J Prod Econ. 129(1):157–168.

Yang Z, Ghahramani A, Becerik-Gerber B. 2016. Building occupancy diversity and HVAC (heating, ventilation, and air conditioning) system energy efficiency. Energy. 109:641–649.

Yuwono M, Guo Y, Wall J, Li J, West S, Platt G, Su SW. 2015. Unsupervised feature selection using swarm intelligence and consensus clustering for automatic fault detection and diagnosis in heating ventilation and air conditioning systems. Appl Soft Comput. 34:402–425.

Yüksek I. 2015. The evaluation of building materials in terms of energy efficiency. Period Polytech Civil Eng. 59(1):45–58.

Zadeh LA. 1965. Fuzzy sets. Inf Control. 8(3):338–353.

Zadeh LA. 1975. The concept of a linguistic variable and its application to approximate reasoning—I. Inf Sci. 8(3):199–249.

Zavadskas EK, Cavallaro F, Podvezko V, Ubarte I, Kaklauskas A. 2017. MCDM assessment of a healthy and safe built environment according to sustainable development principles: A practical neighborhood approach in Vilnius. Sustainability. 9(5):702.

Zuo J, Zhao ZY. 2014. Green building research–current status and future agenda: a review. Renew Sustain Energy Rev. 30:271–281.