https://doi.org/10.1016/j.jairtraman.2017.10.005

Multi-Attribute Sustainability Evaluation of Alternative Aviation Fuels based on Fuzzy ANP and Fuzzy Grey Relational Analysis

Lihong Chen[1], Jingzheng Ren[2]

[1]School of Geography, Geomatics and Planning, Jiangsu Normal University, Xuzhou 221116, China

[2]Department of Industrial and Systems Engineering, The Hong Kong Polytechnic University, Hong Kong SAR, China

Post address: Department of Industrial and Systems Engineering, The Hong Kong Polytechnic University, Hong Kong SAR, China

*Corresponding author (Ren. J).

Email address: renjingzheng123321@163.com; jzhren@polyu.edu.hk

Abstract: The objective of this study is to develop a multi-attribute sustainability evaluation model for assessing the sustainability of various alternative aviation fuels. Fuzzy Analytic Network Process (ANP) which can incorporate the interdependences and interactions among the criteria was used for weights determination. Fuzzy Grey Relational Analysis (FGRA) was employed to determine the integrated priority of each alternative aviation fuel. Four alternative aviation fuels (petroleum refining -A_1, Fischer-Tropsch synthesis based on natural gas -A_2, algal-based fuel -A_3, and soybean -based fuel -A_4) were studied by the model, the sustainability order from the best to the worst determined based on the preferences/opinions of the three groups of stakeholders/decision-makers was Algal-based fuel (A_3), soybean -based fuel (A_4), petroleum refining (A_1), and Fischer-Tropsch synthesis based on natural gas (A_2). The method presented in this study was validated by comparing the results determine by the proposed method with that determined fuzzy TOPSIS and fuzzy sum weighted method, and the results in the case study were also validated by a programming based multi-criteria decision-making which partially using the real data to determine the sustainability order of the four aviation fuels. In order to investigate the effects of the weights on the sustainability order, sensitivity analysis was also carried out in this study.

Keywords: Aviation fuel; sustainability; multi-criteria decision analysis; fuzzy Analytic Network Process; fuzzy grey relational analysis

1. Introduction

Aviation industry has a significant presence in the world's economy, generating USD $664 billion of gross domestic production (GDP) globally (Air Transport Action Group, 2017) . Aviation industry provides nearly 63 million jobs and carries 3.6 billion passengers worldwide (Air Transport Action Group, 2017). With the increase of the number of passengers carried and the growing amount of goods transported by aviation, the demand for aviation fuels is also going to rise in the foreseen future (Nygren *et al.*, 2009). Aviation fuels consist of two main types: 1) jet fuel used for turbine engines, and 2) aviation gasoline for piston engine. Jet fuel is the main aviation fuel type that is used in all large aircrafts. Jet fuel is originating from crude oil. The fossil fuel dominated aviation industry is thus responsible for about 2% of all human-induced carbon oxidized (CO_2) emissions and 12% of all transport sources (Air Transport Action Group, 2017). In addition to the CO_2 emission, aviation has even larger effect on the environmental due to the emission of NO_x, H_2O and sulphate etc. The impact of these emissions varies, for detailed estimation see Blakey *et al*. (2011). Furthermore, crude oil is a kind of limited natural resource subject to depletion, and therefore, the current use of aviation fuel can also cause other environmental problems such as land depletion and water pollution. Finally, the reliance on a single fuel source would bring uncertainty on future fuel supply security and operational costs(Rye et al., 2010).

Safety and security of fuel supply are the two main pillars in the development of aviation fuel technology (Rye et al., 2010). With the expansion of airports world-widely and the increase of the concerns on environment, the environmental footprint of aviation becomes an important dimension for the aviation fuel technology(Rye et al., 2010). The invention of gas turbine engine or 'turbojet' can also promote the healthy development of aviation fuel technology. Turbojet engines are more tolerant of fuel properties compared with piston engines, and can ease the constraints in the fuel system and the operational requirements (Maurice *et al.*, 2001). Besides the production of aviation fuels from traditional distilled crude products, some other alternative ways such as the conversion of coal, gas and biomass to aviation fuels were also applied in aviation fuel industry recently. These alternative aviation fuels can diversify the sources of aviation fuels, thus, it facilitates improving the aviation fuel supply security and/or reduce the environmental impacts. Both efficient air traffic management and alternative fuels are beneficial for achieving sustainable aviation industry. The development of advanced aviation fuel technologies enables the development carbon-natural aviation industry (Blakey et al., 2011). There are usually various alternative aviation fuels which can be selected as the power of aircrafts. The report of MIT PARTNER Center (2009) demonstrated that refinement of some new feedstocks for some alternative aviation fuels produces similar or slightly higher lifecycle emissions comparing with the refinement of the conventional crude oil. Thus, the trade-off decision among the technological performance, costs, availability, safety as well as sustainability should be made when selecting the mot suitable alternative aviation fuels. As discussed above, different aviation fuels perform different on environmental, economic, social, and some other aspects. Although the new alternative aviation fuels may have relatively better environmental performances, they may also perform worse in some other aspects compared with the traditional aviation fuels. Therefore, it is difficult for the users to select the best or the most suitable aviation fuel when facing multiple conflict objectives/criteria, because it is a typical multi-attribute decision analysis problem.

In order to help the stakeholders/decision-makers to select the most sustainable aviation fuel among various choices, a group fuzzy multi-attribute sustainability assessment model which can incorporate the preferences and opinions of different groups of stakeholders/decision-makers was developed by combining fuzzy ANP and fuzzy GRA method. Besides the introduction section, this study has been organized as follows: section 2 carried out comprehensive literature reviews; section 3 presented in the multi-attribute sustainability evaluation model for assessing the sustainability of various alternative aviation fuels by combining fuzzy ANP and FGRA; four representative aviation fuel pathways were studied by the proposed model in Section 4; Section 5 discussed the results through validations and sensitivity analysis; Section 6 concluded this study.

2. Literature reviews

There are various multi-attribute decision analysis (MADA) methods have been used for selecting the best or the most suitable fuel or alternative vehicle among multiple alternatives, and the results were summarized in Table 1.

Among these literatures, Tzeng *et al*. (2005) used AHP to determine the weights of the evaluation criteria for selecting the alternative-fuel modes, TOPSIS and VIKOR methods were compared to determine the best compromise alternative fuel model. Sakthivel *et al.* (2015) applied the hybrid multi-criteria decision analysis method by combining Analytic Network Process (ANP) with TOPSIS and VIKOR methods to evaluate the optimum blend of biodiesel. Paul *et al.* (2015) determined the weights of the criteria by using AHP, and ranked the alternative fuels by using Multi-objective Optimization on the Basis of Ratio Analysis (MOORA) and PROMETHEE methods. The determination of the data of the alternative fuels with respect to the evaluation indicators is prerequisite before using all these methods for determining the sustainability order of the alternative fuels. However, it is usually difficult or even impossible for the users to use exact data with units to describe the performances of the alternative fuels with respect to the evaluation indicators. For instance, Sehatpour *et al*. (2017) employed the PROMETHEE method to evaluate the alternative fuels used in light-duty vehicles including compressed form of natural gas (CNG), liquid petroleum gas (LPG), diesel, methanol, ethanol, biodiesel, biogas, and hydrogen, and crisp numbers were used to rate the alternative fuels with respect to the evaluation indicator. While it is also difficult for the users to use crisp numbers to rate the alternatives, and fuzzy set theory which has the ability to address the ambiguity and vagueness existing in human's judgments has been widely incorporated in MADA for fuel selection. For instance, Ren and Liang (2017) employed the fuzzy logarithmic least squares method to determine the weights of the criteria for sustainability assessment of marine fuels, and fuzzy TOPSIS method was then employed to determine the sustainability order of marine fuels. Ren and Lützen (2017) used fuzzy AHP to determine the weights of the criteria for sustainability assessment of alternative energy sources for shipping, and the MADA method combining with Dempster-Shafer theory was employed to rank the alternative energy sources for shipping. The selection of the most sustainable aviation fuel among multiple choices is similar to the selection of the most sustainable marine fuel, because it is usually difficult for the users to obtain the exact data of the alternative aviation fuels with respect to the evaluation indicators. In addition, the selection of aviation fuel usually involves multiple groups of stakeholders, i.e. air transport administrators, aviation fuel engineers, scholars of air transport management, and investor of air transport, etc.. Thus, the selection of the most sustainable aviation fuel based on group decision-making which can incorporate the preferences and opinions of all the representative stakeholders is of vital importance. To the best of our knowledge, it lack the studies focusing on developing the fuzzy MADA method which can achieve group decision-making and help the stakeholders/decision-makers to select the most sustainable fuel among multiple alternatives. Therefore, this study aims at developing a fuzzy group multi-attribute sustainability assessment model which can incorporate the preferences and opinions of the stakeholders of different groups and allows the users to use fuzzy numbers to rate the alternative aviation fuels with respect to the evaluation indicators, for helping the stakeholders to select the most sustainable aviation fuel among multiple choices.

Table 1: The summary of the MADA methods used for fuel or alternative vehicle selection

Author (year)	Title	Methods	Results
Tzeng *et al*. (2005)	Multi-criteria analysis of alternative-fuel buses for public transportation	AHP, TOPSIS, and VIKOR	Hybrid electric bus is the most suitable for Taiwan urban areas in the short and median term
Mohamadabadi *et al.* (2009).	Development of a multi-criteria assessment model for ranking of renewable and non-renewable transportation fuel vehicles	PROMETHEE	Hybrid vehicle was ranked first followed by biodiesel-based vehicle
Sakthivel *et al.* (2015)	A hybrid multi-criteria decision modeling approach for the best biodiesel blend selection based on ANP-TOPSIS analysis	ANP,TOPSIS, and VIKOR	The optimum fuel blend in fish oil biodiesel for the IC engine is the option with diesel added in the ratio of 20%
Yavuz *et al.* (2015).	Multi-criteria evaluation of alternative-fuel	Hierarchical hesitant fuzzy linguistic model	Electric vehicle has been recognized as the best followed by

	vehicles via a hierarchical hesitant fuzzy linguistic model		biodiesel, CNG and LPG based vehicles.
Paul *et al.* (2015)	Eclectic decision for the selection of tree borne oil (TBO) as alternative fuel for internal combustion engine	AHP,MOORA, and PROMETHEE	Mahua blend is the most appropriate alternative fuel
Sehatpour *et al.* (2017)	Evaluation of alternative fuels for light-duty vehicles in Iran using a multi-criteria approach	PROMETHEE	The compressed natural gas and liquid petroleum gas are the most suitable alternative fuels for light-duty vehicles in Iran,
Ren and Liang (2017))	Measuring the sustainability of marine fuels: A fuzzy group multi-criteria decision making approach	Fuzzy logarithmic least squares method and fuzzy TOPSIS	Hydrogen fuel has been recognized as the most sustainable marine fuel for shipping
Ren and Lützen (2017	Selection of sustainable alternative	Fuzzy AHP, multi-criteria decision-	nuclear power has been recognized as the

	energy source for shipping: Multi-criteria decision making under incomplete information	making method that combines Dempster-Shafer theory	most sustainable alternative energy source for shipping

In the selection of the most sustainable aviation fuel, there are usually two main tasks: one is to determine the weights of the evaluation criteria for selecting the fuels, another is to rank the alternative fuels according to their superiority, i.e. sustainability, integrated performance, and life cycle environmental impact. As for weights determining, Analytic Hierarchy Process (AHP) and various method derived from AHP (i.e. fuzzy AHP) were the most commonly used, but there are also some drawbacks in these methods, i.e. the difficulty in determining the comparison matrix because of the vagueness and ambiguity existed in the opinions of the decision-makers and the lack of considering the interactions and interdependences among the evaluation criteria. In order to address these two drawbacks simultaneously, the fuzzy Analytic Network Process (ANP) method based on comparison judgment matrices was developed for weights determination in this study. As for ranking the alternative fuels, the traditional MADA methods (i.e. PROMETHEE, TOPSIS and VIKOR) sometime do not work well due to the lack of data and information. Thus, fuzzy set theory was usually combined to address this. Accordingly, various fuzzy MADA methods, i.e. fuzzy TOPSIS, fuzzy VIKOR, fuzzy PROMETHEE, and fuzzy grey relational analysis (GRA), were developed. In this study, fuzzy grey relational analysis (FGRA) which can determine the integrated superiority of each alternative fuel was employed to determine the sustainability sequence of the alternative aviation fuels.

3. Methods

In this study, a fuzzy ANP based on comparison judgment matrices which allows the users to use fuzzy numbers to compare the relative importance between each pair of indicators and can incorporate the interdependences and interactions among the indicators was developed for determining the weights of the indicators for sustainability assessment of alternative aviation fuels, and fuzzy GRA method which allows the users to use linguistic terms to rate the alternative aviation fuels with respect to the evaluation indicators was employed to rank the sustainability order of the alternative aviation fuels. The framework of this study has been presented in Figure 1.

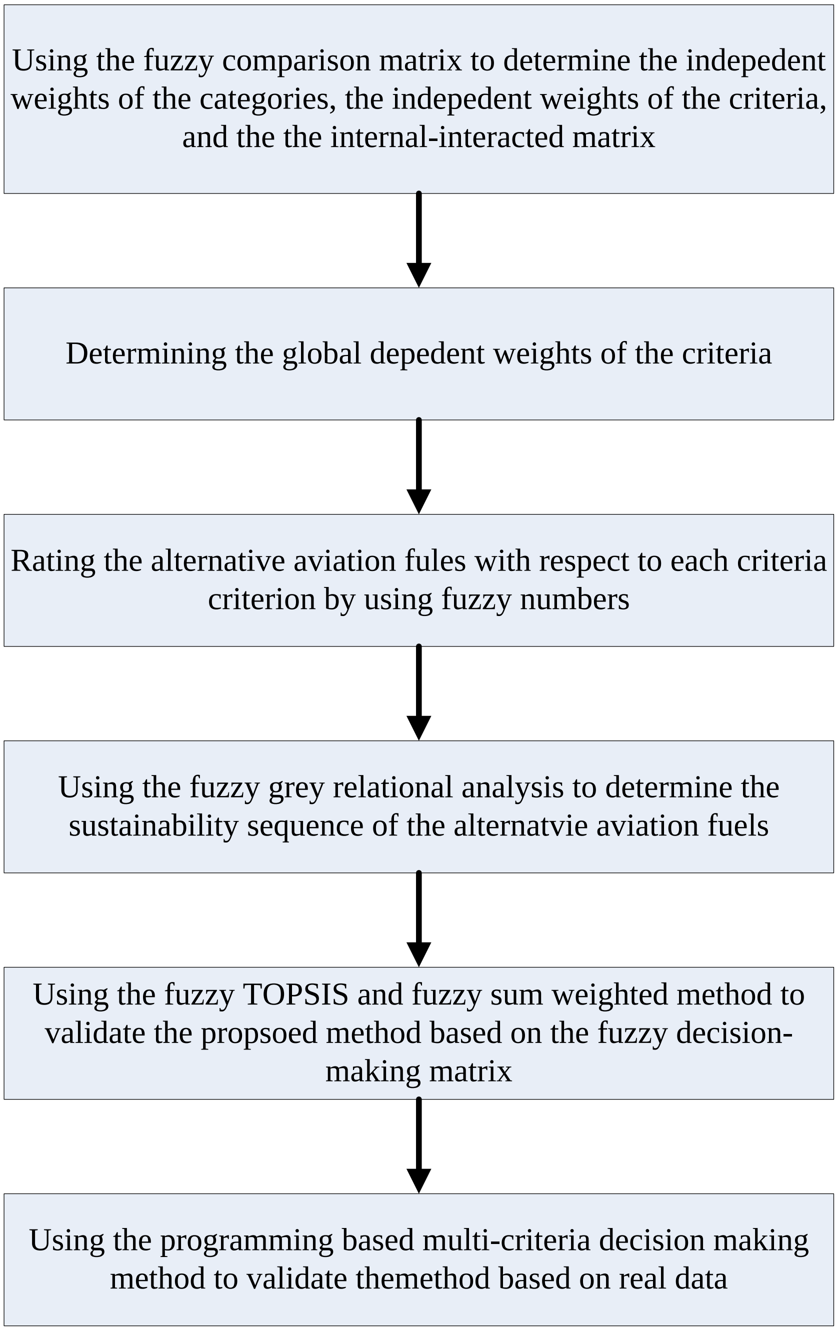

Figure 1: The framework of this study

This section has been organized as follows: section 3.1 presented the preliminary about fuzzy set theory, i.e. the concept of fuzzy set, the arithmetic operations, and the comparison judgment matrix, etc., was firstly introduced. Subsequently, fuzzy Analytic Hierarchy Process (AHP) based on comparison judgment matrices was presented in section 3.2; then, the fuzzy Analytic Network

Process (ANP) method based on comparison judgment matrices was developed in section 3.3; finally, fuzzy grey relational analysis (FGRA) was presented in section 3.4.

3.1 Preliminary

Definition 1 Fuzzy number (Van Laarhoven and Pedrycz, 1983)

Assuming $\tilde{c} = \left(c^1, c^2, c^3\right)$ is a triangular fuzzy number, c^1, c^2, and c^3 which satisfy $c^1 \le c^2 \le c^3, c^1, c^2, c^3 \in R$,are the three elements of the fuzzy number. The membership function of this fuzzy number $\mu_{\tilde{c}}(x)$: $R \to \left[0,1\right]$was presented in Eq.1.

$$\mu_{\tilde{a}}(x) = \begin{cases} 0 & x < c^1, x > c^3 \\ \dfrac{x - c^1}{c^2 - c^1} & c^1 \le x \le c^2 \\ \dfrac{x - c^3}{c^2 - c^3} & c^2 \le x \le c^3 \end{cases} \qquad (1)$$

c^1 and c^3 are the lower and upper bounds, and they can represent the fuzzy degree, and the greater the value of $c^3 - c^1$, the bigger the fuzzy degree.

Definition 2 Arithmetic operations

The arithmetic operations involving fuzzy numbers were presented in Table 2.

Table 2: The arithmetic operations involving fuzzy numbers

$\tilde{c}_1 = \left(c_1^1, c_1^2, c_1^3\right)$ and $\tilde{c}_2 = \left(c_2^1, c_2^2, c_2^3\right)$ are two fuzzy numbers, λ is a crisp number		
Type	Formulas	Equation
Addition	$\tilde{c}_1 + \tilde{c}_2 = \left(c_1^1, c_1^2, c_1^3\right) + \left(c_2^1, c_2^2, c_2^3\right) = \left(c_1^1 + c_2^1, c_1^2 + c_2^2, c_1^3 + c_2^3\right)$	Eq.2
Multiplication	$\tilde{c}_1 \times \tilde{c}_2 = \left(c_1^1, c_1^2, c_1^3\right) \times \left(c_2^1, c_2^2, c_2^3\right) = \left(c_1^1 c_2^1, c_1^2 c_2^2, c_1^3 c_2^3\right)$	Eq.3
	$\tilde{c}_1 \times \lambda = \left(c_1^1, c_1^2, c_1^3\right) \times \lambda = \left(\lambda c_1^1, \lambda c_1^2, \lambda c_1^3\right)$	Eq.4
Reciprocal	$\left(\tilde{c}_1\right)^{-1} = \left[\left(c_1^1, c_1^2, c_1^3\right)\right]^{-1} = \left(\frac{1}{c_1^3}, \frac{1}{c_1^2}, \frac{1}{c_1^1}\right)$	Eq.5

References: Gupta(1985), Kauffman and Gupta (1991)

Definition 3 Comparison judgment matrix (Xu,2002)

Assuming that $\tilde{E} = \left\{\tilde{e}_{ij}\right\}_{n \times n}$ is a judgments for comparing the relative importance/priority of n elements, and $\tilde{e}_{ij} = \left(e_{ij}^1, e_{ij}^2, e_{ij}^3\right)$ which is the element in cell (i,j) of the judgment matrix represents the relative importance/priority of the element i over the element j. If this judgment matrix satisfies the following three conditions (see Eqs.6-8).

$$e_{ij}^1 + e_{ji}^3 = e_{ij}^2 + e_{ji}^2 = e_{ij}^3 + e_{ji}^1 = 1 \tag{6}$$

$$e_{ii}^1 = e_{ii}^2 = e_{ii}^3 = 0.5 \tag{7}$$

$$0 \le e_{ii}^1 \le e_{ii}^2 \le e_{ii}^3 \qquad i, j = 1, 2, \cdots, n \tag{8}$$

Definition 4 The possibility of one triangular fuzzy number greater than another (Xu,2002; Wei, 2010)

The possibility of $\tilde{c}_1=\left(c_1^1,c_1^2,c_1^3\right)$ being greater than $\tilde{c}_2=\left(c_2^1,c_2^2,c_2^3\right)$ was defined in in Eq.9.

$$P\left(\tilde{c}_1\geq\tilde{c}_2\right)=\lambda\max\left\{1-\max\left[\frac{c_2^2-c_1^1}{c_1^2-c_1^1+c_2^2-c_2^1},0\right],0\right\}+ \\ \left(1-\lambda\right)\max\left\{1-\max\left[\frac{c_2^3-c_1^2}{c_1^3-c_1^2+c_2^3-c_2^2},0\right],0\right\} \tag{9}$$

where λ which is a constant represents the attitudes of the decision-makers on the risk. When $\lambda>0.5$, it means that the decisions pursues the risk; when $\lambda<0.5$, it means that the decision-makers dislike the risk; while, $\lambda=0.5$, it means that the decision-makers are neutral to the risk.

Similarly, The possibility of $\tilde{c}_2=\left(c_2^1,c_2^2,c_2^3\right)$being greater than $\tilde{c}_1=\left(c_1^1,c_1^2,c_1^3\right)$can be determined by Eq.10.

$$P\left(\tilde{c}_2\geq\tilde{c}_1\right)=\lambda\max\left\{1-\max\left[\frac{c_1^2-c_2^1}{c_2^2-c_2^1+c_1^2-c_1^1},0\right],0\right\}+ \\ \left(1-\lambda\right)\max\left\{1-\max\left[\frac{c_1^3-c_2^2}{c_2^3-c_2^2+c_1^3-c_1^2},0\right],0\right\} \tag{10}$$

Theorem 1 $\tilde{c}_1=\left(c_1^1,c_1^2,c_1^3\right)$ and $\tilde{c}_2=\left(c_2^1,c_2^2,c_2^3\right)$ are two triangular fuzzy numbers, the possibility satisfies:

$$0\leq P\left(\tilde{c}_1\geq\tilde{c}_2\right)\leq 1, 0\leq P\left(\tilde{c}_2\geq\tilde{c}_1\right)\leq 1 \tag{11}$$

$$P\left(\tilde{c}_1\geq\tilde{c}_2\right)=1 \quad if \quad c_1^1\geq c_2^3 \text{ and } P\left(\tilde{c}_2\geq\tilde{c}_1\right)=1 \quad if \quad c_2^1\geq c_1^3 \tag{12}$$

$$P\left(\tilde{c}_1 \geq \tilde{c}_2\right) = 0 \quad if \quad c_1^3 \leq c_2^1 \text{ and } P\left(\tilde{c}_2 \geq \tilde{c}_1\right) = 0 \quad if \quad c_2^3 \leq c_1^1 \tag{13}$$

$$P\left(\tilde{c}_1 \geq \tilde{c}_2\right) + P\left(\tilde{c}_2 \geq \tilde{c}_1\right) = 1 \tag{14}$$

3.2 Fuzzy AHP based on comparison judgment matrix

The fuzzy AHP based on comparison judgment matrix consists of four steps based on Xu (2002) and Wei (2010), and they are: determining the comparison judgment matrices using words (Step 1), transforming the words in comparison judgment matrices into fuzzy numbers (Step 2), determining the aggregated judgment matrix (Step 3), determining the fuzzy weights (Step 4), determining the possibility matrix (Step 5), and calculating the crisp weights (Step 6).

Step 1: determining the comparison judgment matrices using words. The words presented in Table 1 can help the users to determine the comparison judgment matrices by all the decision-makers. For example, if the relative importance of a criterion over another by a decision-maker is “Weakly important (WE)”, and “WE” will be put in the corresponding cell of the matrix.

Step 2: transforming the words in comparison judgment matrices into fuzzy numbers. The words used in the comparison judgment matrices determined in Step 1 can be transformed into fuzzy numbers according to Table 3. For example, “WE” corresponds to the triangular fuzzy number

(0.5, 0.6, 0.7).

The comparison judgment matrix determined by the decision-makers was presented in Eq.15.

Table 3: Fuzzy scales for determining the comparison judgment matrices

Linguistic Terms	Abbreviation	Fuzzy numbers
Equally important	EQ	(0.5, 0.5,0.5)
Weakly important	WE	(0.5,0.6,0.7)
Moderately important	MO	(0.6,0.7,0.8)
Strongly important	ST	(0.7,0.8,0.9)
Very strong important	VS	(0.8,0.9,0.9)
Significantly important	SI	(0.9,1.0,1.0)
The comparison terms of the above	C-	The comparison element with respect to the above mentioned fuzzy numbers can be determined by Eq.6

Reference: adapted from Xu (2002) and Wei (2010)

After determining $\tilde{m}_{ij}$, $\tilde{m}_{ji}$ can be determined by Eq.6.

$$\tilde{M} = \begin{vmatrix} (0.5,\ 0.5,0.5) & \tilde{m}_{12} & \tilde{m}_{13} & \cdots & \tilde{m}_{1n} \\ - & (0.5,\ 0.5,0.5) & \tilde{m}_{23} & \cdots & \tilde{m}_{2n} \\ - & - & (0.5,\ 0.5,0.5) & \cdots & \tilde{m}_{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ - & - & - & \cdots & (0.5,\ 0.5,0.5) \end{vmatrix} \tag{15}$$

where $\tilde{M}$ is the comparison judgment matrix, $\tilde{m}_{ij}(i=1,2,\cdots,n;\ j=1,2,\cdots,n)$ is the element in cell (i,j) in the aggregated matrix, and m_{ij}^1, m_{ij}^2, and m_{ij}^3 are the three elements of the fuzzy number $\tilde{m}_{ij}(i=1,2,\cdots,n;\ j=1,2,\cdots,n)$.

Step 4: determining the fuzzy weights. The fuzzy weights of the n elements can be calculated by Eq.16 according to Buckley (1985).

$$\tilde{\omega}_i = \frac{\prod_{j=1}^{n} \tilde{m}_{ij}}{\sum_{i}^{n} \prod_{j=1}^{n} \tilde{m}_{ij}} = \left(\omega_i^1, \omega_i^2, \omega_i^3\right) \tag{16}$$

Step 5: determining the possibility matrix. After determining the fuzzy weights of the n elements, the possibility degree of the weight of one criterion being greater than that of another criterion can be determined by Eq.10, all the possibility degrees can form a possibility matrix, as presented in Eq.17.

$$P = \begin{vmatrix} 0.5 & p_{12} & p_{13} & \cdots & p_{1n} \\ p_{21} & 0.5 & p_{23} & \cdots & p_{2n} \\ p_{31} & p_{32} & 0.5 & \cdots & p_{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ p_{n1} & p_{n2} & p_{n3} & \cdots & 0.5 \end{vmatrix} \tag{17}$$

where $p_{ij}(i = 1, 2, \cdots, n; j = 1, 2, \cdots, n)$ represents the possibility degree of the weight of the *i*-th criterion being greater than that of the *j*-th criterion.

Step 6: calculating the crisp weights. After obtaining the possibility matrix in Step 5, the crisp weights of each element can be calculated according to Xu (2001), as presented in Eq.18.

$$\omega_i = \frac{1}{n(n-1)}\left(\sum_{j=1}^{n} p_{ij} + \frac{n}{2} - 1\right) \tag{18}$$

where ω_i represents the weight of the *i*-th element.

3.3 Fuzzy Analytic Network Process (ANP)

AHP and various methods for weights calculation derived from AHP usually set a hypothetical condition that all the criteria are independent and neglect the interactions and interdependences among the criteria. However, the criteria weights determined under this set hypothetical condition cannot fully reflect the relative importance or the preferences of the users. Accordingly, Analytic Network Process (ANP) which uses 'network' to substitute the word 'hierarchy' for incorporating the independences among the evaluation criteria was developed to weights determination. There are usually two types of ANP methods, one is to create the super-matrix in which the relative influences of all the criteria on each criterion can be incorporated, and another is based on the matrix operations and performs a pair-wise comparison of the criteria on each criterion, and this method is more convenient for the users to conduct and they do not need to determine the super-matrix (Shahabi *et al.*, 2014). Thus, the thoughts of the second type of ANP were adopted in this study for developing a fuzzy ANP for determining the weights of the indicators for sustainability assessment.

In this study, the fuzzy ANP based on the comparison judgment matrix was developed for calculating the weights of the criteria for assessing the sustainability of alternative aviation fuels. Assuming that there are a total of K categories, and a total of K_L indicators in the L-th (L=1, 2,…,K) category for assessing the sustainability of alternative aviation fuels, the fuzzy ANP consists of four steps for determining the relative weights of the indicators under the condition of considering the interrelationships and interactions among these indicators (Shahabi *et al.*, 2014; Dağdeviren and Yüksel, 2010).

Step 1: Using the group fuzzy AHP method to calculate the independent weights of the K categories and that of the indicators in each category.

$$W = \left[W_1, W_2, \cdots, W_K\right] \tag{19}$$

where W represents the independent weight vector of the K categories, and $W_L \, (L = 1, 2, \cdots, K)$ represents the independent weight of the *L*-th (L=1,2,…,K) category

$$\varpi_L = \left[\varpi_1, \varpi_2, \cdots, \varpi_{K_L}\right] \tag{20}$$

where ϖ_L is the independent weight vector for the indicators in the *L*-th category, and $\varpi_{p,L} \left(p = 1, 2, \cdots, K_L\right)$ represents the independent weight of the p-th indicator in the *L*-th category.

Step 2: Using the group fuzzy AHP method to calculate the internal-interacted matrix for depicting the interdependences and interactions among the K categories.

The internal-interacted matrix was presented in Eq.26. The vector of the L-th column in this matrix represents the interdependence and interaction of all the other categories on the L-th category.

$$IIM = \begin{vmatrix} iim_{11} & iim_{12} & iim_{13} & \cdots & iim_{1K} \\ iim_{21} & iim_{22} & iim_{23} & \cdots & iim_{2K} \\ iim_{31} & iim_{32} & iim_{33} & \cdots & iim_{3K} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ iim_{K1} & iim_{K2} & iim_{K3} & \cdots & iim_{KK} \end{vmatrix} \tag{21}$$

where IIM is the internal-interacted matrix, and $iim_{L_1L_2} \left(L_1 = 1, 2, \ldots, K; L_2 = 1, 2, \ldots, K\right)$ represents the relative effect of category L_1 on category L_2 .

Step 3: Determining the interdependent weights of the K categories.

The interdependent weights of the K categories can be determined by Eq.22 according to Yüksel and Dagˇdeviren (2007).

$$WI = IIM \times W \;\; = \begin{vmatrix} iim_{11}+1 & iim_{12} & iim_{13} & \cdots & iim_{1K} \\ iim_{21} & iim_{22}+1 & iim_{23} & \cdots & iim_{2K} \\ iim_{31} & iim_{32} & iim_{33}+1 & \cdots & iim_{3K} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ iim_{K1} & iim_{K2} & iim_{K3} & \cdots & iim_{KK}+1 \end{vmatrix} \times \begin{vmatrix} W_1 \\ W_2 \\ \vdots \\ W_{K-1} \\ W_K \end{vmatrix} \qquad (22)$$

where $WI = \left[wi_1, wi_2, \cdots, wi_K\right]$ is the interdependent weight vector, and $wi_L \left(L = 1, 2, \cdots, K\right)$ represents the interdependent weight of the L-th category.

The interdependent weights can be normalized according to Eq.23.

$$\omega_i' = \frac{wi_i}{\sum_{i=1}^{n} wi_i} \qquad (23)$$

where ω_i' represents the normalized independent weight of the *i*-th category.

Step 4: Determining the global weights of the indicators considering the he interrelationships and interactions among them.

The global weights of the indicators considering the interrelationships and interactions among them can be determined by calculating the product of the local weight of the indicator and the interdependent normalized weight of the corresponding category.

The difference of the proposed fuzzy ANP from some other methods is that the proposed method uses a fuzzy AHP method to determine the independent weights and the elements in the internal-interacted matrix. In the proposed fuzz AHP, the users can use the linguistic terms to establish the comparison matrix, and the weights determined by this method are all crisp numbers.

3.4 Fuzzy Grey Rational Analysis

After determining the weights of the evaluation criteria using the methods presented in section 2.2 and 2.3, Fuzzy Grey Rational Analysis (FGRA) was applied for determining the sustainability order of the alternative aviation fuels because of its advantages: (1) achieving multi-criteria sustainability measurements of aviation fuels under the conditions of uncertainties and lacking information; (2) providing an integrated superiority index as the sustainability performance of alternative aviation fuel.

There are four steps in the FGRA method based on the work of Wei (2010), including determining the decision-making matrix (Step 1), standardization (Step 2), generating the reference series (Step 3), calculating the grey relational coefficients (Step 4), and determining the integrated superiority of each alternative (Step 5).

Step 1: determining the decision-making matrix.

The first step of the FGRA method is to determine the decision-making matrix, as presented in Eqs.23-24. $\tilde{a}_{ij}(i=1,2,\cdots,m; j=1,2,\cdots,n)$ in the cell (i,j) in the aggregated decision-making matrix can be determined by the users according to the fuzzy numbers for depicting the performances of the alternatives (Table 4).

$$D=\begin{vmatrix} \tilde{a}_{11} & \tilde{a}_{12} & \tilde{a}_{13} & \cdots & \tilde{a}_{1n} \\ \tilde{a}_{21} & \tilde{a}_{22} & \tilde{a}_{23} & \cdots & \tilde{a}_{2n} \\ \tilde{a}_{31} & \tilde{a}_{32} & \tilde{a}_{33} & \cdots & \tilde{a}_{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \tilde{a}_{m1} & \tilde{a}_{m2} & \tilde{a}_{m3} & \cdots & \tilde{a}_{mn} \end{vmatrix} \quad (23)$$

$$\tilde{a}_{ij} = \left(a_{ij}^1, a_{ij}^2, a_{ij}^3\right) \tag{24}$$

where D is the decision-making matrix for the multi-attribute decision making problem with m alternatives and n criteria, $\tilde{a}_{ij}(i = 1, 2, \cdots, m; j = 1, 2, \cdots, n)$ represents the weighted attribute value of the *j*-th attribute under the *i*-th alternative, and a_{ij}^1, a_{ij}^2 ,and a_{ij}^3 are the three elements of $\tilde{a}_{ij}$.

Table 4: Fuzzy numbers for rating the performances of the alternatives

Performances	Abbreviation	Fuzzy numbers
Very weak	VW	(0,0,0.15)
Weak	W	(0,0.15,0.30)
Medium weak	MW	(0.15,0.30,0.50)
Medium	M	(0.30,0.50,0.65)
Medium High	MH	(0.50,0.65,0.80)
High	H	(0.65,0.80,1.00)
Very High	VH	(0.80,1.00,1.00)

Reference: Elevli, 2014.

Step 2: standardization.

The data presented in the fuzzy decision-making matrix can be standardized by Eqs.25-27.

$$\tilde{b}_{ij} = \left(b_{ij}^1, b_{ij}^2, b_{ij}^3\right) \tag{25}$$

As for the benefit-type indicators,

$$\begin{cases} b_{ij}^{1} = \dfrac{a_{ij}^{1}}{\sqrt{\sum_{i=1}^{m}\left(a_{ij}^{3}\right)^{2}}} \\ b_{ij}^{2} = \dfrac{a_{ij}^{2}}{\sqrt{\sum_{i=1}^{m}\left(a_{ij}^{2}\right)^{2}}} \\ b_{ij}^{3} = \dfrac{a_{ij}^{3}}{\sqrt{\sum_{i=1}^{m}\left(a_{ij}^{1}\right)^{2}}} \end{cases} \qquad i = 1, 2, \cdots, m;\ j = 1, 2, \cdots, n \tag{26}$$

As for the cost-type indicators,

$$\begin{cases} b_{ij}^{1} = \dfrac{\dfrac{1}{a_{ij}^{3}}}{\sqrt{\sum_{i=1}^{m}\left(\dfrac{1}{a_{ij}^{1}}\right)^{2}}} \\ b_{ij}^{2} = \dfrac{\dfrac{1}{a_{ij}^{2}}}{\sqrt{\sum_{i=1}^{m}\left(\dfrac{1}{a_{ij}^{2}}\right)^{2}}} \\ b_{ij}^{3} = \dfrac{\dfrac{1}{a_{ij}^{1}}}{\sqrt{\sum_{i=1}^{m}\left(\dfrac{1}{a_{ij}^{3}}\right)^{2}}} \end{cases} \qquad i = 1, 2, \cdots, m;\ j = 1, 2, \cdots, n \tag{27}$$

Step 3: generating the reference series.

The reference series which consist of the ideal solutions with respect to all the indicators can be determined according to Eqs.28-29.

$$b_j^* = \left(\max_{i=1,2,\cdots,m} b_{ij}^1, \max_{i=1,2,\cdots,m} b_{ij}^2, \max_{i=1,2,\cdots,m} b_{ij}^3 \right) = \left(b_j^{*1}, b_j^{*2}, b_j^{*3} \right) \tag{28}$$

$$B^* = \begin{bmatrix} b_1^* & b_2^* & \cdots & b_n^* \end{bmatrix} \tag{29}$$

where B^* represents the reference series, and $b_j^* (j = 1, 2, \cdots, n)$ represents the maximum standardized value of the *j*-th criterion.

Step 4: calculating the grey relational coefficients.

The grey relational coefficients can be calculated by Eqs.30-31.

$$\xi_{ij} = \frac{\min_i \min_j \Delta_{ij} + \rho \max_i \max_j \Delta_{ij}}{\Delta_{ij} + \rho \max_i \max_j \Delta_{ij}} \tag{30}$$

$$\Delta_{ij} = \sqrt{\frac{1}{3}\left[\left(b_{ij}^1 - b_j^{*1} \right)^2 + \left(b_{ij}^2 - b_j^{*2} \right)^2 + \left(b_{ij}^3 - b_j^{*3} \right)^2 \right]} \tag{31}$$

where $\rho \in [0,1]$ is the distinguishing coefficient.

As for the distinguishing coefficient, Shen *et al.* (2003) suggested to take the value of 0.05 to match the principle in statistics though most of the literatures take the value of 0.5.

Step 5: determining the integrated superiority of each alternative and ranking them.

The integrated superiority of each alternative can be determined by Eq.32.

$$S_i = \sum_{j=1}^{n} \xi_{ij} \omega_j \qquad i = 1, 2, \cdots, m \tag{32}$$

where S_i represents the integrated superiority of the *i*-th alternative, and ω_j is the weight of the *j*-th indicator.

The priority order of the alternative could be obtained after determining the integrated superiority of each alternative, and the rule is that the greater the value of S_i, the better the *i*-th alternative will be.

4. Case study

In order to show how to use the developed method for assessing the sustainability of the alternative aviation fuels, four representative fuel pathways, including petroleum refining (A_1), Fischer-Tropsch synthesis based on natural gas (A_2), algal-based fuel (A_3), and soybean -based fuel (A_4) were studied in this section, and the following scenarios were specified as follows:

• Petroleum refining (A_1): aviation gasoline (avgas) which was refined from petroleum, is an aviation fuel used in spark-ignited internal-combustion engines to propel aircraft, and the main petroleum component used in blending avgas is alkylate (Zahran *et al*., 2017);

• Fischer-Tropsch synthesis based on natural gas (A_2): the Fischer-Tropsch synthesis method was used to produce aviation fuel from syngas (CO and H_2) through catalytic conversion of syngas derived from natural gas (Hari *et al*., 2015; Zhao *et al*., 2016);

• Algal-based fuel (A_3): this scenario used the energy crop-algal to produce the crude oil, and then to produce aviation fuel through hydrogenization (Zhao *et al*., 2016), and the hydroprocessed renewable jet fuels are generally paraffinic liquids with the chemical formula of C_nH_{2n+2}.

• Soybean -based fuel (A_4): soybean was firstly used to produce biofuel which is alkyl esters of fatty acid through the process of transesterification (Hari *et al*., 2015), and then to produce aviation fuel through hydrogenization (Zhao *et al*., 2016).

The sustainability order of these four alternative aviation fuels were determined by the proposed multi-criteria decision making method in this study. The concept of sustainability or sustainable development usually emphases great economic benefits, low environmental impacts, and high social acceptability, namely the so-called “triple bottom lines (TBL)” (Rodger and George, 2017; Ren *et al*., 2015). Accordingly, the indicators for sustainability assessment should represent the three pillars of sustainability, namely economic, environmental, and social aspects. And the indicator selection was based on five principles, namely “system principle (the indicators should roundly reflect the essential characteristics of sustainability)”, “consistency principle (the indictors should be consistent to the objective of sustainability assessment)”, “measurability principle (the indicators selected should be measurable quantitatively or qualitatively)”, and “comparability principle (the alternative aviation fuels should be comparable with respect to the indicators)” (Wang *et al*., 2009; Ren and Lützen, 2017). Based on these five principles, a total of ten indicators in three categories (economy, environment and society) were selected to assess the sustainability of the four alternative aviation fuels, as presented in Table 5.

Table 5: The indicators for assessing the sustainability of the alternative aviation fuels

Categories	Indicators	Definitions	References
Economic (C_1)	Capital cost	The costs for facilities and factories building to produce aviation fuels	Ren *et al.*, 2013
	Production cost per unit (C_{11})	The cost for the production of per unit aviation fuel	Ren *et al.*, 2015
	Energy consumption (C_{12})	The energy consumed in the whole life cycle of aviation fuel production, and the less energy consumption, the greater the energy efficiency	Ren *et al.*, 2016
Environment (C_2)	GHG emissions (C_{13})	The global warming potential contributed by the emissions during the whole life cycle of aviation fuels	Zhao *et al.*, 2016
	Water consumption (C_{21})	The total water consumption during the whole life cycle of aviation fuels	Zhao *et al.*, 2016
	PM10 (C_{22})	PM 10 emissions during the whole life cycle of aviation fuels	Zhao *et al.*, 2016
	PM2.5 (C_{23})	PM 2.5 emissions during the whole life cycle of aviation fuels	Zhao *et al.*, 2016
Society (C_3)	Social acceptability	The social acceptance of the aviation fuel	Ren *et al.*, 2013
	Innovation on technology	The innovations compared with the traditional aviation heavy oils	Ren *et al.*, 2013; Ren *et al.*, 2016

Technology maturity	The degree of maturity of the technology referring how widespread at both international and national levels	Ren *et al*., 2013; Ren *et al*., 2016

As for the selection of the stakeholders, the “representative principle” which means that the preferences and opinions of different representative stakeholders should be incorporated in sustainability ranking of the alternative fuels for aviation, was employed for selecting the stakeholders. Accordingly, the selected experts should represent all the stakeholders with different preferences/willingness, and each representative group of stakeholders should have the same preferences/willingness. Therefore, a focus group meeting was held for decision making in which three groups of representative stakeholders participating in assessing the sustainability of these four alternative aviation fuels in this study, and they are user and manager group (S#1), engineer and scholar group (S#2), and passenger and customer group(S#3). The user and manager group consists of four staffs working in the airports (two administrator and two crew of airport who worked for more than five years in airports), the engineer and scholar group consists of two engineers of aviation fuel production who worked for more than ten years and two professors whose research focuses on clean aviation fuels and working for more than twenty years in universities, and the passenger and customer group consists of four passengers of air transport (including a 18-year-old young passenger, two middle-aged passengers, and an old passenger). The three groups of stakeholders were invited to participate in a seminar held in 18 November 2016, at Chongqing University (Chongqing, China) for discussing the sustainability of the four alternative aviation fuels, and they firstly used the linguistic terms to establish the comparison judgment matrices for determining the weights of the three categories and that of the indicators in each category. It is worth pointing out that the comparison judgment matrices determined by different groups of stakeholders may be different, because different groups of stakeholders have different preferences and willingness, and the average comparison judgment matrix can be used to determine the weights of the three categories as well as that of the indicators in each category.

Taking the calculation of the weights of the three categories as an example, the comparison judgment matrices using the linguistic terms were firstly determined by the three groups of stakeholders in the seminar, as presented in Table 6.

Table 6: The comparison judgment matrix using linguistic terms for determining the weights of three categories

	Economic(C_1)	Environment(C_2)	Society (C_3)
Economic(C_1)	EQ	CMO	WE
Environment(C_2)	MO	EQ	ST
Society (C_3)	CWE	CST	EQ

After that, the comparison judgment matrix using fuzzy numbers for determining the weights of three categories can be determined, as presented in Table 7.

Table 7: The comparison judgment matrix using fuzzy numbers for determining the weights of three categories

	Economic(C_1)	Environment(C_2)	Society (C_3)
Economic(C_1)	(0.5, 0.5,0.5)	(0.2,0.3,0.4)	(0.5,0.6,0.7)
Environment(C_2)	(0.6,0.7,0.8)	(0.5, 0.5,0.5)	(0.7,0.8,0.9)
Society (C_3)	(0.3,0.4,0.5)	(0.1,0.2,0.3)	(0.5, 0.5,0.5)

According to Eq.16, the fuzzy weights of three categories can be determined, and the results were presented in Table 8. According to Eq.10 and Eq.17 (with the assumption that $\lambda = 0.5$), the possibility matrix which consists of the possibility degree of the weight of one category being greater than that of another category can be determined, and the results were presented in Eq.33. Then, the crisp weights of three categories can be determined by Eq.18, and the results were also presented in Table 7.

$$\begin{vmatrix} 0.5 & 0 & 0.9168 \\ 1.0 & 0.5 & 1.0 \\ 0.0832 & 0 & 0.5 \end{vmatrix} \tag{33}$$

Table 8: Fuzzy weights and the crisp weights of the three categories

	Economic(C_1)	Environment(C_2)	Society (C_3)
Fuzzy weights	(0.0870, 0.2195,0.5091)	(0.3652,0.6829,1.3091)	(0.0261,0.0976,0.2727)
Crisp weights	0.3195	0.5000	0.1805

In a similar way, the weights of the indicators in each category can also be obtained, and the results were presented in Table 9.

Table 9: The local weights of the indicators in each category

	C_{11}	C_{12}	C_{13}		Weights
Capital cost (C_{11})	(0.5, 0.5,0.5)	(0.3,0.4,0.5)	(0.6,0.7,0.8)		0.3838
Production cost per unit (C_{12})	(0.5,0.6,0.7)	(0.5, 0.5,0.5)	(0.5,0.6,0.7)		0.4448
Energy consumption (C_{13})	(0.2,0.3,0.4)	(0.3,0.4,0.5)	(0.5, 0.5,0.5)		0.1714
	C_{21}	C_{22}	C_{23}	C_{24}	Weights
GHG emissions (C_{21})	(0.5, 0.5,0.5)	(0.7,0.8,0.9)	(0.3,0.4,0.5)	(0.2,0.3,0.4)	0.2229
Water consumption (C_{22})	(0.1,0.2,0.3)	(0.5, 0.5,0.5)	(0.1,0.2,0.3)	(0.1,0.1,0.2)	0.1250
PM10 (C_{23})	(0.5,0.6,0.7)	(0.7,0.8,0.9)	(0.5, 0.5,0.5)	(0.3,0.4,0.5)	0.2894
PM2.5 (C_{24})	(0.6,0.7,0.8)	(0.8,0.9,0.9)	(0.5,0.6,0.7)	(0.5, 0.5,0.5)	0.3627
	C_{31}	C_{32}	C_{33}		Weights
Social acceptability (C_{31})	(0.5, 0.5,0.5)	(0.5,0.6,0.7)	(0.1,0.2,0.3)		0.2498
Innovation on technology (C_{32})	(0.3,0.4,0.5)	(0.5, 0.5,0.5)	(0.2,0.3,0.4)		0.2502
Technology maturity (C_{33})	(0.7,0.8,0.9)	(0.6,0.7,0.8)	(0.5, 0.5,0.5)		0.5000

After determining the effects of the three categories on each of them, the internal-interacted matrix for depicting the interdependences and interactions among the three categories can also be determined, and the results were presented in Table 10 and Eq.34, respectively.

Table 10: The effects of the three categories on each of them

Effects on C_1	Economic(C_1)	Environment(C_2)	Society (C_3)	Weights
Economic(C_1)	(0.5, 0.5,0.5)	(0.6,0.7,0.8)	(0.3,0.4,0.5)	0.3697
Environment(C_2)	(0.2,0.3,0.4)	(0.5, 0.5,0.5)	(0.2,0.3,0.4)	0.1667
Society (C_3)	(0.5,0.6,0.7)	(0.6,0.7,0.8)	(0.5, 0.5,0.5)	0.4636
Effects on C_2	Economic(C_1)	Environment(C_2)	Society (C_3)	Weights
Economic(C_1)	(0.5, 0.5,0.5)	(0.5,0.6,0.7)	(0.7,0.8,0.9)	0.4663
Environment(C_2)	(0.3,0.4,0.5)	(0.5, 0.5,0.5)	(0.7,0.8,0.9)	0.3670
Society (C_3)	(0.1,0.2,0.3)	(0.1,0.2,0.3)	(0.5, 0.5,0.5)	0.1667
Effects on C_3	Economic(C_1)	Environment(C_2)	Society (C_3)	Weights
Economic(C_1)	(0.5, 0.5,0.5)	(0.7,0.8,0.9)	(0.5,0.6,0.7)	0.4947
Environment(C_2)	(0.1,0.2,0.3)	(0.5, 0.5,0.5)	(0.3,0.4,0.5)	0.1667
Society (C_3)	(0.3,0.4,0.5)	(0.5,0.6,0.7)	(0.5, 0.5,0.5)	0.3386

$$\begin{vmatrix} 0.3697 & 0.4663 & 0.4947 \\ 0.1667 & 0.3670 & 0.1667 \\ 0.4636 & 0.1667 & 0.3386 \end{vmatrix} \quad (34)$$

The interdependent weights of the three categories can be obtained according to Eq.22, and they can also be normalized according to Eq.23, the results were presented in Table 11.

Table 11: The interdependent weights of the three categories and the normalized interdependent weights of the three categories

	Economic(C_1)	Environment(C_2)	Society (C_3)
Interdependent weights	0.7601	0.7669	0.4731
Normalized interdependent weights	0.3800	0.3834	0.2365

Then, the global weights of the ten indicators can be determined. For instance, the global weight of capital cost is: 0.3800×0.3838=0.1458. Accordingly, the global weights of all the ten indicators determined by fuzzy ANP can also be obtained, and the results were presented in Table 12. According to Tables 8-9, the global weights of all the ten indicators without the considerations of the interrelationships among the ten criteria determined by fuzzy AHP can also be determined (see Table 12).

Table 12: The global weights of the ten indicators with and without the considerations of the interrelationships among the criteria

Indicators	C_{11}	C_{12}	C_{13}	C_{21}	C_{22}	C_{23}	C_{24}	C_{31}	C_{32}	C_{33}
Weights by fuzzy ANP	0.1458	0.1690	0.0651	0.0855	0.0479	0.1110	0.1391	0.0591	0.0592	0.1182
Weights by fuzzy AHP	0.1226	0.1421	0.0548	0.1114	0.0625	0.1447	0.1814	0.0451	0.0452	0.0902

The experts were also asked to use the linguistic terms to rate the alternatives with respect to each of the evaluation indicators, and it is also worth pointing out that the decision-making matrix determined by different groups of stakeholders may also be different, because different groups of stakeholders have different views and opinions, and the average decision-making matrix can be employed to rank the alternative aviation fuels. The average decision-making matrix using fuzzy numbers was presented in Table 13.

Table 13: The decision-making matrix using fuzzy numbers

	A_1	A_2	A_3	A_4
Capital cost (C_{11})	(0,0.15,0.30)	(0.15,0.30,0.50)	(0.30,0.50,0.65)	(0.30,0.50,0.65)
Production cost of per unit fuel (C_{12})	(0.80,1.00,1.00)	(0.65,0.80,1.00)	(0.15,0.30,0.50)	(0.15,0.30,0.50)
Energy consumption (C_{13})	(0.65,0.80,1.00)	(0.30,0.50,0.65)	(0,0,0.15)	(0,0.15,0.30)
GHG emissions (C_{21})	(0.30,0.50,0.65)	(0.30,0.50,0.65)	(0.65,0.80,1.00)	(0.80,1.00,1.00)
Water consumption (C_{22})	(0,0,0.15)	(0.65,0.80,1.00)	(0.50,0.65,0.80)	(0,0.15,0.30)
PM10 (C_{23})	(0,0.15,0.30)	(0,0,0.15)	(0.30,0.50,0.65)	(0.30,0.50,0.65)
PM2.5 (C_{24})	(0.15,0.30,0.50)	(0,0.15,0.30)	(0.50,0.65,0.80)	(0.30,0.50,0.65)
Social acceptability (C_{31})	(0,0,0.15)	(0.30,0.50,0.65)	(0.80,1.00,1.00)	(0.50,0.65,0.80)
Innovation on technology(C_{32})	(0,0,0.15)	(0.15,0.30,0.50)	(0.80,1.00,1.00)	(0.65,0.80,1.00)
Technology maturity (C_{33})	(0.80,1.00,1.00)	(0.80,1.00,1.00)	(0.50,0.65,0.80)	(0.65,0.80,1.00)

Note: petroleum refining (A_1), Fischer-Tropsch synthesis based on natural gas (A_2), algal-based fuel (A_3), and soybean -based fuel (A_4)

Then, the Fuzzy Grey Rational Analysis was employed to determine the sustainability order of the four alternative aviation fuels, and the results were presented in Figure 2.

Integrated superiority

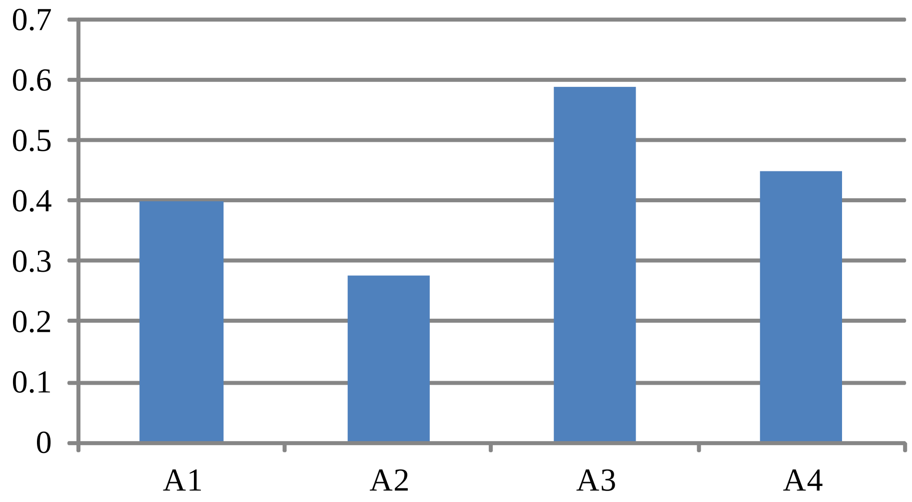

Figure 2: The integrated superiority of the four aviation fuels

Algal-based fuel (A_3) was identified as the most sustainable, followed by soybean -based fuel (A_4), petroleum refining (A_1), and Fischer-Tropsch synthesis based on natural gas (A_2). Therefore, the development of algal-based aviation fuel should be highly promoted for enhancing the sustainability of air transportation. However, it is worth pointing out that the algal-based aviation fuel is not competitive compared with some other aviation fuels, because it does not perform well in economic and technological aspects, especially the production cost of per unit fuel is relatively higher than some other aviation fuels due to the immature technology. Accordingly, the improvement of the technology maturity and the reduction of production cost of per unit fuel are critical for enhancing the competitiveness of algal-based aviation fuel.

5. Discussions

The sustainability of the four alternative aviation fuels were also assessed by the fuzzy sum weighted method (FSWM) and fuzzy Technique for Order Preference by Similarity to an Ideal

Solution (FTOPSIS) based on the standardized decision-making matrix. The weighted sum of the four alternative aviation fuels determined by FSWM was presented in Table 14. In order to determine the sustainability order of the four alternative aviation fuels, Eq.9 was employed to compare the values of the weighted sum with respect to the four alternative aviation fuels, and the results were presented in Eq.35.

Table 14: The weighted sum of the four alternative aviation fuels

	A_1	A_2	A_3	A_4
Weighted sum	(0.2021,0.3746,0.7034)	(0.2118,0.3836,0.7503)	(0.2951,0.5208,0.9671)	(0.2523,0.4813,0.9218)

$$P = \begin{vmatrix} 0.5000 & 0.4663 & 0.2176 & 0.2967 \\ 0.5337 & 0.5000 & 0.2525 & 0.3305 \\ 0.7824 & 0.7475 & 0.5000 & 0.5692 \\ 0.7033 & 0.6695 & 0.4308 & 0.5000 \end{vmatrix} \tag{35}$$

According to Eq.35, if $P\left(A_i > A_j\right) > 0.5$, it means that A_i is more superior to A_j; if $P\left(A_i > A_j\right) = 0.5$, it means that A_i is indifferent to A_j; if $P\left(A_i > A_j\right) < 0.5$, it means that A_i is inferior to A_j. It could be obtained that the sustainability order from the most sustainable to the least determined by FSWM is $A_3 > A_4 > A_1 > A_2$.

In the FTOPSIS method, the elements in the standardized decision-making matrix were firstly defuzzied, and the traditional TOPSIS was then the closeness coefficients of each alternative aviation fuel can be then determined, and they are 0.3747, 0.3788, 0.4520, and 0.4234, respectively. Accordingly, it could also be obtained that the sustainability order from the most sustainable to the least determined by FTOPSIS is $A_3 > A_4 > A_2 > A_1$.

The results determined by FTOPSIS are the same with that determined by FGRA, and the results determined by FSWM are also consistent to that determined by the fuzzy grey relational analysis method, and both algal-based fuel (A_3) and soybean-based fuel (A_4) were recognized as the most sustainable and the secondly most sustainable, respectively. However, there are also some difference, because petroleum refining (A_1) and Fischer-Tropsch synthesis based on natural gas (A_2) was ranked in the third position by SWM and FGRA, respectively (see Table 15). Therefore, it could be summarized that the sustainability order of the four alternative aviation fuels determined by FGRA and FTOPSIS are the same, and algal-based fuel (A_3) and soybean-based fuel (A_4) were recognized as the most sustainable ones by all these three MCDM methods; however, the results determined by FGRA and FTOPSIS are slightly different from that determined by FSWM, and the reason is simple-FSWM method merely determines the priorities of the four alternative aviation fuels by simply calculating the weighted sum of the data with respect to the evaluation metrics, but both the FGRA and FTOPSIS employed the reference series to determine the relative priorities of the four alternative aviation fuels which can effectively eliminate the influences of the units.

Table 15: The comparison of the results determined by FGRA, FTOPSIS, and FSWM

	A_1	A_2	A_3	A_4
Sustainability order by FGRA	4	3	1	2
Sustainability order by FTOPSIS	4	3	1	2
Sustainability order by FSWM	3	4	1	2

Besides the validation of the developed FGRA method, these four alternative aviation fuels were also ranked based on the real data presented in the work of Zhao et al. (2016). The programming based multi-criteria decision making method was employed to rank the four alternative aviation fuels, the readers can refer to the work of Ren *et al*. (2013) for more details of this method. The sustainability sequence of the four aviation fuels determined by the programming based multi-criteria decision making method was presented in Table 16. It is apparent that the sustainability sequence of the four aviation fuels based on the real data is the same with the proposed method in this study. The main difference of the programming based multi-criteria decision making method for ranking the four alternatives from the proposed method in this study is that the proposed method ranks the four aviation fuels based on the subjective judgments of the decision-makers, while the ranking by the programming based multi-criteria decision making method was based the real data of the four alternative aviation fuels. To some extent, the correctness of the developed method for sustainability ranking of alternative aviation fuels can be validated.

Table 16: The sustainability sequence of the four aviation fuels based on the programming based multi-criteria decision making method

Alternatives	A_1	A_2	A_3	A_4
Ranking	4	3	1	2

Sensitivity analysis was implemented to investigate the effects of the weights (relative importance) on the final sustainability ranking of the four alternative aviation fuels, and the following thirteen cases were studied:

Base Case: The weights determined by fuzzy ANP presented in this study;

Case 1: The weights determined by fuzzy AHP presented in this study;

Case 2: Equal weights- $\omega_{11} = \omega_{12} \cdots = \omega_{42} = \omega_{43} = 0.1000$; and

Case 3-12: A dominant weight and an equal weight to all the other indicators. A dominant weight to the *i*-th indicator and an equal weight to all the other indicators - $\omega_i = 0.4600$, and the other nine indicators were assigned a weight-0.0600. It is worth pointing out that cases 3-12 were designed based on two principles in this study: (i) the dominant weight should be greater than the weight of each of the other criteria; and (ii) the dominant weight should be less than the sum of the weights of the other nine criteria. In such a case, two objectives can be guaranteed, one is to guarantee that one criterion among the ten criteria was given dominant priority, and another is to guarantee that the relative importance of the dominant criterion cannot exceed the sum of the relative importance of the other nine criteria.

The results of sensitivity analysis were presented in Figure 3. According to the results of sensitivity analysis, it could be concluded that the weights (relative importance) of the indicators have significant effects on the final sustainability ranking of the alternative aviation fuels. Accordingly, the users should firstly to assure the accuracy and correctness of determining the weights of the indicators for sustainability assessment of aviation fuels. However, algal-based fuel (A_3) has been recognized the most sustainable aviation fuel for seven times in these twelve cases, it has also been recognized as the secondly most sustainable aviation fuel for four times, and it has been ranked in the third position in the last case. Therefore, it could be concluded that the ranking of algal-based fuel as one of the most sustainable aviation fuels is robust. Similarly, Fischer-Tropsch synthesis based on natural gas (A_2) was recognized as the worst pathway for aviation fuel in most of the cases, and this also demonstrates the correctness, accuracy, and feasibility of fuzzy GRA for ranking the alternative aviation fuels.

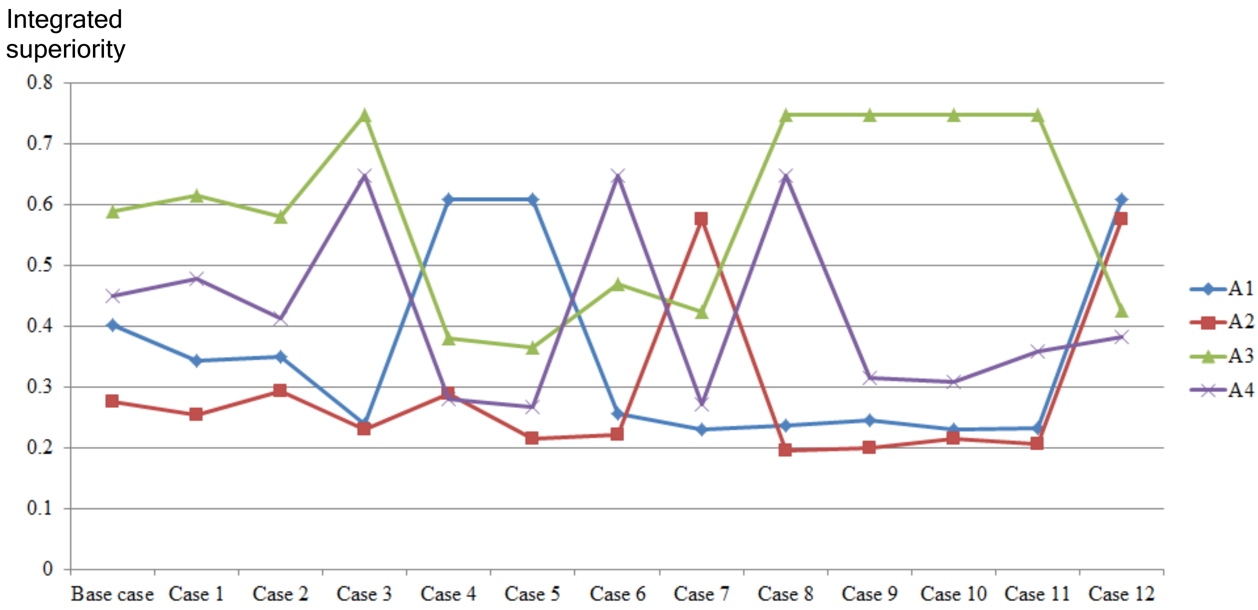

Figure 3: The results of sensitivity analysis

6. Conclusion and policy implications

In order to help the decision-makers to select the most sustainable aviation fuel among several alternatives, a multi-attribute sustainability assessment method was developed to rank the alternative aviation fuels according to their sustainability performances. The fuzzy ANP method based on the comparison judgment matrices was employed to determine the relative weights of the indicators for assessing the sustainability of the aviation fuels. Fuzzy grey relational analysis was used to determine the integrated superiorities of the aviation fuels.

Four alternative aviation fuels were assessed by the developed method in this study, and the results reveal that the proposed method can successfully determine the sustainability order of multiple aviation fuels. The sustainability order from the best to the worst is algal-based fuel (A_3), soybean -based fuel (A_4), petroleum refining (A_1), and aviation fuel from Fischer-Tropsch synthesis based on natural gas (A_2). Moreover, the integrated priorities of algal-based fuel (A_3) and soybean-based fuel (A_4) are much greater than that of the other two aviation fuel scenarios.

Accordingly, the policy-makers should take effective actions and draft targeted policies for promoting the development of algal-based fuel and soybean-based fuel. The following implications were recommended for promoting the development of algal-based and soybean-based aviation fuels:

(1) Setting special grants/funds for Research, Development and Demonstration (RD&D) of algal-based and soybean-based aviation fuels to overcome the weak points (i.e. relatively higher production cost and lower technology maturity) of these two aviation fuel scenarios;
(2) Drafting effective industry policies for financial support for promoting the development of algal-based and soybean-based aviation fuels, i.e. zero interest loan and subsidies for the corporate which produce or use algal-based and soybean-based aviation fuels.

The developed fuzzy group sustainability evaluation model study has the following innovations compared with the previous studies:

(1) The incorporation of the interdependences and interactions among the sustainability criteria: the fuzzy ANP which can incorporate the interdependences and interactions among the indicators for sustainability assessment of aviation fuels was developed for determining the weights;
(2) The incorporation of the preferences of different stakeholders: a fuzzy group MADA method was proposed based on fuzzy GRA which allows multiple stakeholders to participate in the decision-making was employed for ranking the alternative aviation fuels, and the sustainability order of the alternative aviation fuels can be determined;
(3) The decision-making was based on the judgments of the decision-makers: the users are allowed to use linguistic terms and fuzzy numbers to rate the alternative aviation fuels with respect to the evaluation indicators, and the decision can be made without the real data.

Besides the theoretical contributions, the developed fuzzy group decision-making method for ranking the alternative aviation fuels is a generic method, and it can be popularized to some other cases. The decision-makers are also allowed to add more criteria for sustainability assessment of more alternative aviation fuels. However, the proposed method cannot effectively use the real data for decision-making, and this lead to the loss of some real information, because the ranking of the alternative aviation fuels was based on subjective judgments of the decision-makers rather than the real data. Therefore, the future work is to develop a multi-criteria decision making method which can address both the real data and the fuzzy numbers for rating the alternatives with respect to some evaluation criteria, for ranking the alternative aviation fuels.

Acknowledgment

This study was financially supported by The Start-up Grant of The Hong Kong Polytechnic University for New Employees (Project title: ***Multi-criteria Decision Making for More Sustainable Transportation,*** project account code: **1-ZE8W**).

References

Air Transport Action Group. (2017). Facts and Figures. Retrieved from http://www.atag.org/facts-and-figures.html

Blakey, S., Rye, L., Wilson, C. W. (2011). Aviation gas turbine alternative fuels: A review. Proceedings of the Combustion Institute, 33(2), 2863-2885.

Buckley, J.J., 1985. Fuzzy hierarchical analysis. Fuzzy Set Syst, 17, 233–247.

Dağdeviren, M., Yüksel, İ., 2010. A fuzzy analytic network process (ANP) model for measurement of the sectoral competititon level (SCL). Expert Systems with Applications 37(2), 1005-1014.

Elevli, 2014. Logistics freight center location decision by using Fuzzy-PROMETHEE. Transport, 29(4), 412-418.

Gupta, M. M., 1985. Introduction to fuzzy arithmetic: Theory and applications. New York, NY: Van Nostrand Reinhold Company.

Hari, T. K., Yaakob, Z., Binitha, N. N. (2015). Aviation biofuel from renewable resources: routes, opportunities and challenges. Renewable and Sustainable Energy Reviews, 42, 1234-1244.

Kauffman, A., Gupta, M. M., 1991. Introduction to fuzzy arithmetic: theory and application.

Maurice, L. Q., Lander, H., Edwards, T., & Harrison Iii, W. E. (2001). Advanced aviation fuels: a look ahead via a historical perspective. Fuel, 80(5), 747-756. Nygren, E., Aleklett, K., & Höök, M. (2009). Aviation fuel and future oil production scenarios. Energy Policy, 37(10), 4003-4010.

MIT PARTNER Center. (2009, 25-27 May). U.S. Fuel Trends Analysis. Paper presented at the the Fourth Meeting of the Group on International Aviation and Climate Change (GIACC/4-I/P12), Montréal, Canada.

Mohamadabadi, H. S., Tichkowsky, G., Kumar, A. (2009). Development of a multi-criteria assessment model for ranking of renewable and non-renewable transportation fuel vehicles. Energy, 34(1), 112-125.

Paul, S., Sarkar, B., Bose, P.J., 2015. Eclectic decision for the selection of tree borne oil (TBO) as alternative fuel for internal combustion engine. Renewable and Sustainable Energy Reviews 48, 256-263.

Ren, J., Fedele, A., Mason, M., Manzardo, A., Scipioni, A. (2013). Fuzzy multi-actor multi-criteria decision making for sustainability assessment of biomass-based technologies for hydrogen production. International Journal of hydrogen energy, 38(22), 9111-9120.

Ren, J., Manzardo, A., Mazzi, A., Zuliani, F., Scipioni, A. (2015). Prioritization of bioethanol production pathways in China based on life cycle sustainability assessment and multicriteria decision-making. The International Journal of Life Cycle Assessment, 20(6), 842-853.

Ren, J., Xu, D., Cao, H., Wei, S. A., Dong, L., Goodsite, M. E. (2016). Sustainability decision support framework for industrial system prioritization.AIChE Journal, 62(1), 108-130.

Ren, J., Liang, H. (2017). Measuring the sustainability of marine fuels: A fuzzy group multi-criteria decision making approach. Transportation Research Part D: Transport and Environment, 54, 12-29.

Ren, J., Lützen, M. (2017). Selection of sustainable alternative energy source for shipping: Multi-criteria decision making under incomplete information. Renewable and Sustainable Energy Reviews, 74, 1003-1019.

Rodger, J. A., George, J. A. (2017). Triple bottom line accounting for optimizing natural gas sustainability: A statistical linear programming fuzzy ILOWA optimized sustainment model approach to reducing supply chain global cybersecurity vulnerability through information and communications technology. Journal of Cleaner Production, 142, 1931-1949.

Rye, L., Blakey, S., & Wilson, C. W. (2010). Sustainability of supply or the planet: a review of potential drop-in alternative aviation fuels. *Energy & Environmental Science*, *3*(1), 17-27. doi:10.1039/B918197K

Sakthivel, G., IIangkumaran, M., Gaikward, A., 2015. A hybrid multi-criteria decision modeling approach for the best biodiesel blend selection based on ANP-TOPSIS analysis. Ain Shams Engineering Journal 6(1), 239-256.

Sehatpour, M.H., Kazemi, A., Sehatpour, H., 2017. Evaluation of alternative fuels for light-duty vehicles in Iran using a multi-criteria approach. Renewable and Sustainable Energy Reviews 72, 295-310.

Shahabi, R. S., Basiri, M. H., Kahag, M. R., Zonouzi, S. A., 2014. An ANP–SWOT approach for interdependency analysis and prioritizing the Iran′ s steel scrap industry strategies. Resources Policy, 42, 18-26.

Shen, M., Xue, X., Zhang, X., 2003. Determination of discrimination coefficient in grey incidence analysis. Journal of Air Force Engineering University (Natural Science Edition), 4(1), 68-70. (in Chinese).

Tzeng, G.H., Lin, C.W., Opricovic, S., 2005. Multi-criteria analysis of alternative-fuel buses for public transportation. Energy Policy, 33(11), 1373-1383.

Van Laarhoven, P. J. M., Pedrycz, W., 1983. A fuzzy extension of Saaty's priority theory. Fuzzy sets and Systems, 11(1-3), 229-241.

Wang, J. J., Jing, Y. Y., Zhang, C. F., Zhao, J. H. (2009). Review on multi-criteria decision analysis aid in sustainable energy decision-making. Renewable and Sustainable Energy Reviews, 13(9), 2263-2278.

Wei, G.W., 2010. Theory and methods of multiple attribute decision making based on fuzzy information. China Economic Publishing House, Beijing, China. (in Chinese).

Xu, 2001. Algorithm for priority of fuzzy comparison judgment matrix. Journal of Systems Engineering, 16(4), 311-314. (in Chinese)

Xu, Z., 2002. A method for priorities of triangular fuzzy number comparison judgment matrices. Fuzzy Systems and Mathematics, 16(1), 47-50. (in Chinese).

Yavuz, M., Oztaysi, B., Onar, S. C., Kahraman, C. (2015). Multi-criteria evaluation of alternative-fuel vehicles via a hierarchical hesitant fuzzy linguistic model. Expert Systems with Applications, 42(5), 2835-2848.

Yüksel, İ., Dagˇdeviren, M., 2007. Using the analytic network process (ANP) in a SWOT analysis – A case study for a textile firm. Information Science, 177(16),3364-3382.

Zahran, S., Iverson, T., McElmurry, S. P., Weiler, S. (2017). The effect of leaded aviation gasoline on blood lead in children. Journal of the Association of Environmental and Resource Economists, 4(2), 575-610.

Zhao, J., Guo, F., A, L., Yang, X., 2016. Research of sustainable feedstock for future alternative aviation fuel. Journal of Beijing University of Aeronautics and Astronautics 42 (11), 2379-2384. (in Chinese).