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A fuzzy weighted influence non-linear gauge system with application to advanced technology assessment at NASA

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ABSTRACT

Evaluating the advanced technology projects at NASA is difficult due to multiple and intertwined evaluation criteria and uncertainties inherent in unproven new technologies. The conventional multi-criteria decision-making models often ignore the interdependencies and uncertainties in the evaluation process. We propose a fuzzy Weighted Influence Non-linear Gauge System (WINGS) to evaluate advanced technology projects at the Kennedy Space Center (KSC). The WINGS method uses ideographic causal maps to uncover the intertwined criteria and their causal relations in complex problems. Fuzzy set theory is an effective method that uses fuzzy logic to model uncertainties in ill-defined problems. The fuzzy WINGS method proposed in this study uncovers the interdependencies among the evaluation criteria by identifying the direction of the dependencies (influences) and their intensities, along with the strengths of the evaluation criteria. Fuzzy judgments are used to cope with uncertainties in untested new technologies. The conventional WINGS method does not consider a reference point in the solution space. For this reason, we introduce the concepts of *ideal* and *nadir* solutions, which are new to WINGS, to rank the alternative solutions according to their Euclidean distances from the *ideal* (or *nadir*) solutions. Finally, we present a case study to evaluate ten advanced technology projects based on six intertwined criteria and 38 sub-criteria at the KSC to demonstrate the applicability of the new fuzzy WINGS method proposed in this study.

1. Introduction

Multi-criteria Decision-Making (MCDM) is a popular method for solving complex decision-making problems with multiple and often conflicting criteria. MCDM problems have the following common features (Hwang & Yoon, 1981): multiple and conflicting criteria, incommensurable units of measurement, and solutions that are either designing the best alternative(s) or selecting the best alternative(s) among a finite set of alternatives. MCDM problems are classified as *continuous* or *discrete*. The continuous problems consider a continuous decision space with an emphasis on *optimization*, and the discrete problems consider a discrete decision space with an emphasis on satisfaction. Multi-Objective Decision-Making (MODM) models are used to solve continuous MCDM problems where the goal is to design the best alternative(s) by maximizing or minimizing multiple objectives. Multi-Attribute Decision-Making (MADM) involves making preference decisions over multiple attributes and selecting the best alternative(s) from a predetermined set of alternatives. The Analytic Hierarchy Process (AHP) is the most widely used MADM method in the literature. Best-Worst Method (BWM), The Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS), Analytic Network Process (ANP), Decision-Making Trial and Evaluation Laboratory (DEMATEL), and VIseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) are other well-known MADM methods used in various decision-making problems in the discrete solution space. Applications of MCDM methods have thrived in many scientific fields, including but not limited to banking, education, government, healthcare, manufacturing, non-profit, finance, logistics, energy, transportation, city planning, and

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engineering (Kumar et al., 2017). Readers should refer to (Cinelli et al., 2020) for a comprehensive and state-of-the-art review of MCDM methods.

Fuzzy logic has been commonly used in MCDM. The concept of fuzzy logic was introduced by Zadeh (1965). The fuzzy sets theory is central to the concept of fuzzy logic (Pedrycz and Gomide, 1998). Zarinbal et al. (2014, p. 75) point out fuzzy logic can formalize/mechanize the human abilities to reason and make rational decisions under imprecision and without any measurements or computations. Fuzzy logic allows for handling the concept of partial truths, which is very common in decision-making with uncertain, incomplete, vague, and imprecise information. Fuzzy logic uses a linguistic scale to describe the strength of the cause-effect relationships in MCDM problems with interdependent variables. Fuzzy sets are used to translate this scale into numerical values. Fuzzy logic has been widely used to solve MCDM problems in healthcare, transportation and logistics, risk management, manufacturing, technology management, investment management, environment, energy, human resources management, and education (Zamani-Sabzi et al., 2016).

Frank (1995) proposed an MCDM model to evaluate safety improvement strategies according to cost, safety, and other uncertain factors for flight and Launch vehicles at NASA. Their model used the AHP to select the best safety improvement strategy by balancing safety with quantitative factors of schedule, technical feasibility, performance, mass, cost, and volume. Tavana and Zandi (2012) proposed a fuzzy MCDM model for evaluating a range of potential mission scenarios for the human exploration of Mars formulated at the Mission Operations Directorate at the Johnson Space Center. They used the conjunction method to minimize the number of alternative mission scenarios, the fuzzy Risk Failure Mode and Effects Analysis to study the potential failures in the alternative scenarios, a fuzzy group Real Options Analysis to perform a cost-benefit analysis, and a fuzzy group permutation approach to select the optimal mission scenario. Koc-San et al. (2013) developed an integrated MCDM framework with Geographical Information Systems and AHP for astronomical observatory site selection. Lee et al. (2021) proposed and integrated Strengths, Weaknesses, Opportunities, Threats (SWOT), and AHP to evaluate strategies for accelerating the Korean space and satellite industry's growth by considering various internal strengths and weaknesses and external opportunities and threats.

Tavana and Hatami-Marbini (2011) proposed a group MCDM model to integrate subjective judgments derived from AHP with entropy information and the TOPSIS to evaluate the priority of human spaceflight mission simulators at NASA. Ullah et al. (2013) proposed an MCDM with TOPSIS for space launch vehicle design and evaluation. They used the morphological matrix method and Tsiolkovsky's ideal velocity rocket equation for sizing and performance modeling of space launch vehicles. They then used TOPSIS to rank and identify the most promising alternative design concept. Sánchez-Lozano et al. (2015) proposed a fuzzy MCDM model for selecting the best military training aircraft for the Spanish Air Force. Their proposed models included quantitative technical criteria (i.e., service ceiling, endurance) and qualitative criteria (i.e., human factors, aircraft flying, and handling qualities). They used an integrated model that combined fuzzy logic with AHP and TOPSIS to assess and select the best military training aircraft. In this study, we borrow the concepts of the *ideal* and *nadir* (anti-ideal) solutions from TOPSIS. Hwang and Yoon (1981) introduced TOPSIS for evaluating the performance of alternatives with reference to the ideal and nadir solutions in MCDM problems. According to TOPSIS, the best alternative is the one that is closest to the ideal solution and farthest from the nadir solution. The ideal (best) and nadir (worst) solutions are artificial solutions created for reference purposes.

The AHP is a popular MCDM method introduced by Saaty (1980). The hierarchical structure of AHP allows for visualizing the impact of criteria on the alternatives. The AHP assumes that selection criteria and the alternatives are independent. Tavana (2003) used the AHP, probabilities, the entropy concept, and the maximize-agreement heuristic to enhance the policymakers' intuition at the Kennedy Space Center (KSC) in evaluating advanced technology projects. Tavana (2004a) used an MCDM model with AHP, subjective probabilities, and entropy to identify the risks and benefits associated with three alternative mission architecture scenarios for the human exploration of Mars at NASA. Tavana (2004b) developed an Intelligent Flight Support System (IFSS) to promote situational awareness at NASA's Mission Control Center with an interactive virtual model of the International Space Station to support flight controllers with the planning, communications, command, and control monitoring and troubleshooting. An MCDM model with AHP was designed and implemented to evaluate the effectiveness, systems, flexibility, access, connectivity, change, and cost of the proposed IFSS. Tavana (2006) integrated expert judgments from the AHP with entropy data into an MCDM model to prioritize five mission simulators for the human planetary explorations at the Johnson Space Center. Tavana (2008) developed an MCDM model with AHP at NASA called Fahrenheit 59 for benchmarking global warming in Europe. The model develops benchmark scores that are weighted sum measures of subjective and intrinsic weights and global warming data. Fahrenheit 59 is used to monitor continuous progress towards countering global warming in the European Union countries. Sánchez-Lozano et al. (2019) used AHP in an MCDM model to study the dynamics of asteroids' trajectories and potential threats to the Earth at NASA's Jet Propulsion Laboratory. The Reference Ideal Method considers several near-Earth asteroid impact features (i.e., distance, width, and impact energy). Almahdi et al. (2019) proposed an MCDM with the BWM and VIKOR for evaluating six mobile patient monitoring systems, including one from NASA.

The ANP is a generalization of the AHP that considers complex interdependencies among the decision variables in a hierarchical structure (Saaty, 1996). Tavana et al. (2013) developed a fuzzy group MCDM model for technology assessment at NASA by integrating an ANP model representing the complicated structure of the evaluation criteria and alternatives assessment criteria and alternatives with a fuzzy TOPSIS for advanced-technology project assessment at the KSC. Measuring Attractiveness by a Categorical-Based Evaluation TecHnique (MACBETH) is another MCDM proposed by Bana e Costa and Vansnick (1997). This method uses pairwise comparisons, similar to AHP, but the results are processed according to the measurement theory. Rodriguez et al. (2017) extended the MACBETH method with reasoning maps to captures the interactions and the strength of influence in the model. Dožić et al. (2018) proposed fuzzy AHP and logarithmic fuzzy preference programming methods to choose aircraft types that meet the airline requirements. Ramirez-Atencia et al. (2020) proposed a fuzzy MCDM to evaluate multi-UAV mission planning scenarios and showed the proposed fuzzy method to operate better than operators. The DEMATEL considers interdependencies by visualizing the structure of complex causal relationships in MCDM problems (Fontela and Gabus, 1976). DEMATEL uses a graph to visualize these relationships, with arrows representing the direction of influence and numbers at the nodes represent the intensity of the influence. The Weighted Influence Nonlinear Gauge System (WINGS) method is derived from DEMATEL by Michnik (2013). DEMATEL models the direction and the intensity of the influence in MCDM problems with interdependencies. In contrast, WINGS models the direction and the intensity of the influence plus the strength of the criteria.

This study develops a fuzzy WINGS approach for evaluating advanced technology projects at NASA. The WINGS method is used to uncover the interdependencies among the evaluation criteria by identifying the direction of the dependencies (influences), the intensity of the influences, and the strengths of the evaluation criteria. The fuzzy logic is utilized to handle uncertainties in the performance of unproven and new advanced technology projects in the space industry. The lower- and upper-bound scores in WINGS are problem-specific and vary from one problem to another. While one can compare alternative scores in

Table 1
A comparison between the proposed method and competing methods in the literature.

Author(s)	Method/ Technique/ Approach	Interdependency	Strength of Factor	Influence Intensity	Fuzzy Set	Ideal and Nadir	Case study
Tavana (2003)	AHP and entropy	–	✓	–	–	–	NASA
Tavana and Zandi (2012)	Novel MADM method	–	✓	–	✓	–	NASA
Koc-San et al. (2013)	AHP	–	✓	–	–	–	Astronomical Industry
Abdullah and Zulkifli (2015)	Fuzzy AHP and interval fuzzy DEMATEL	✓	✓	✓	✓	–	Higher Education Industry
Sánchez-Lozano et al. (2015)	AHP and TOPSIS	–	✓	–	✓	✓	Air Force
Gölcük and Baykasoğlu (2016)	ANP and DEMATEL	✓	✓	✓	–	–	–
Pamučar et al. (2017)	ANP and DEMATEL	✓	✓	✓	✓	–	–
Mavi and Standing (2018)	Fuzzy ANP and fuzzy DEMATEL	✓	✓	✓	✓	–	Construction Industry
Acuña-Carvajal et al. (2019)	Fuzzy DEMATEL	✓	–	✓	✓	–	Banking Industry
Almahdi et al. (2019)	BWM and VIKOR	–	✓	–	–	–	NASA
Kaya and Yet (2019)	DEMATEL	✓	–	✓	–	–	Automotive Industry
Sánchez-Lozano et al. (2019)	AHP	–	✓	–	–	–	NASA
Govindan et al. (2020)	BWM and DEMATEL	✓	✓	✓	–	–	Automotive Industry
Kaviani et al. (2020)	BWM and WINGS	✓	✓	✓	–	–	Automotive Industry
Du and Li (2021)	DEMATEL	✓	–	✓	–	–	Automotive Industry
Lee et al. (2021)	SWOT and AHP	–	✓	–	–	–	Space and Satellite Industry
Wang et al. (2021)	WINGS	✓	✓	✓	–	–	Construction Industry
This paper	Fuzzy WINGS	✓	✓	✓	✓	✓	NASA

WINGS for ranking purposes, it is unclear how good or poor a solution is relative to the solution space. For this reason, we introduce the concepts of ideal and nadir alternatives in WINGS to show the relevance of the most suitable solution to other possible solutions in the solution space, including the best (ideal) and the worst (nadir) solutions. In addition, we use the Euclid method (Tavana, 2002) and the concepts of ideal and nadir solutions as a reference point for the first time in this paper to rank the alternatives according to their Euclidean distances from the ideal (or nadir) solutions. Finally, we present a case study to evaluate ten advanced technology projects at the KSC based on six interdependent criteria and 38 sub-criteria to demonstrate the applicability of the fuzzy WINGS method proposed in this study.

The problem of evaluating advanced technology projects at NASA is a complex hierarchical decision problem with multiple and conflicting intertwined criteria. Table 1 shows integrated AHP, ANP, and BWM with DEMATEL have been used in the literature to solve hierarchical decision-making problems with intertwined criteria. Alternatively, the WINGS method can be used to solve these complex problems. The advantage of using WINGS over these integrated methods is computational complexity does not grow substantially when the number of criteria, sub-criteria, or alternatives is increased. However, the WINGS method does not consider the ideal and nadir solutions as reference points and has not been commonly used to solve problems with uncertain solution space. For the first time, this study proposes a fuzzy WINGS method that utilizes the concepts of the ideal and nadir solutions to rank alternatives in uncertain environments. Table 1 highlights the difference between the model proposed in this study and the competing methods in the MCDM literature.

The remainder of this paper is organized as follows. In Section 2, we present the proposed fuzzy WINGS approach. Section 3 presents our numerical examples. In Section 4, we present a case study at NASA's KSC to demonstrate the applicability and efficacy of the method proposed in this study. Section 5 presents our conclusions, managerial implications, and futures research directions.

2. Proposed approach

DEMATEL is an effective structural method for the identification of cause-effect relationships in MCDM problems. DEMATEL discovers the critical criteria in complex intertwined systems by representing the interdependencies among criteria with impact relation diagrams and cause-and-effect matrices. The WINGS method is also a structural model inspired by DEMATEL. While DEMATEL considers the "influence intensity" to capture the impact of one criterion on another, WINGS uses a second measure for the "strength of criteria" in addition to the influence intensity. In this paper, a novel fuzzy WINGS method is presented to handle uncertain, ambiguous, and incomplete data in WINGS. The proposed method is composed of the following eight steps:

Step 1: Experts determine the evaluation criteria.

Step 2: Experts uncover the interdependencies among the evaluation criteria using a casual relation graph. In this graph, nodes represent the evaluation criteria, and relations among the criteria are represented with arrows. For example, Fig. 1 shows that i and j are the selection

Fig. 1. A casual relation representation in WINGS.

Table 2
The fuzzy linguistic scale (Chang et al., 2011).

Linguistic terms	Strength/influence score	Triangular fuzzy numbers
No strength/influence (NO)	0	(0,0,0.25)
Very low strength/influence (VL)	1	(0,0.25,0.5)
Low strength/influence (L)	2	(0.25,0.5,0.75)
High strength/influence (H)	3	(0.5,0.75,1)
Very high strength/influence (VH)	4	(0.75,1,1)

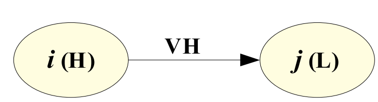


Fig. 2. A casual relation representation in fuzzy WINGS.

criteria, and criteria i is influencing criteria j.

Step 3: Experts specify the criteria' strengths and their influence intensities using the linguistic terms presented in Table 2. As shown in Fig. 2, the strength values are noted inside the nodes, and the influence intensities are noted on the vectors. In this Figure, the strengths of criteria i and j are considered high and low, respectively, and the influence intensity of criterion i on criterion j is considered very high.

It is not always mandatory to use the linguistic terms presented in Table 2; instead, other linguistic terms can be used depending on the problem and the context. We suggest using the same linguistic terms for consistency between the strengths and influences.

Step 4: In this step, the fuzzy direct strength-influence matrix is formed. This matrix is shown by $\widetilde{M} = [(M^l, M^m, M^u)]$ (n represents the number of criteria). In Eq. (1), the general structure of this matrix is presented.

$$\widetilde{M} = \left[\left(M^l, M^m, M^u\right)\right] = \begin{bmatrix} \left(m^l_{11}, m^m_{11}, m^u_{11}\right) & \cdots & \left(m^l_{1j}, m^m_{1j}, m^u_{1j}\right) & \cdots & \left(m^l_{1n}, m^m_{1n}, m^u_{1n}\right) \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \left(m^l_{i1}, m^m_{i1}, m^u_{i1}\right) & \cdots & \left(m^l_{ij}, m^m_{ij}, m^u_{ij}\right) & \cdots & \left(m^l_{in}, m^m_{in}, m^u_{in}\right) \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \left(m^l_{n1}, m^m_{n1}, m^u_{n1}\right) & \cdots & \left(m^l_{nj}, m^m_{nj}, m^u_{nj}\right) & \cdots & \left(m^l_{nn}, m^m_{nn}, m^u_{nn}\right) \end{bmatrix} \tag{1}$$

In this matrix, the strength of criteria is placed on the main diameter, and the influence intensity of criterion i on criterion j is placed in the ith row and jth column of this matrix.

Step 5: In this step, the matrix $\widetilde{M} = [(M^l, M^m, M^u)]$ is normalized using Eq. (2):

$$\begin{aligned} &\widetilde{N} = \left[\left(N^l, N^m, N^u\right)\right] \\ &N^l = \frac{1}{s} M^l \\ &N^m = \frac{1}{s} M^m \\ &N^u = \frac{1}{s} M^u \end{aligned} \tag{2}$$

where $\widetilde{N} = [(N^l, N^m, N^u)]$ represents the fuzzy normalized matrix and s is calculated through Eq. (3):

$$s = \sum_{i=1}^{n} \sum_{j=1}^{n} m^u_{ij} \tag{3}$$

Step 6: In this step, the total fuzzy strength-influence matrix ($\widetilde{T}$) is calculated using Eq. (4):

$$\begin{aligned} &\widetilde{T} = \left[\left(T^l, T^m, T^u\right)\right] \\ &T^l = \frac{N^l}{I - N^l} \\ &T^m = \frac{N^m}{I - N^m} \\ &T^u = \frac{N^u}{I - N^u} \end{aligned} \tag{4}$$

where I represents $n \times n$ identity matrix.

Step 7: In this step, initially, the total impact scores ($\widetilde{r}_i$) and the total receptivity scores ($\widetilde{c}_j$) are calculated using Eqs. (5) and (6), respectively.

$$\begin{aligned} &\widetilde{r}_i = \left[\left(r^l_i, r^m_i, r^u_i\right)\right] \\ &r^l_i = \sum_{j=1}^{n} t^l_{ij}, \quad r^m_i = \sum_{j=1}^{n} t^m_{ij}, \quad r^u_i = \sum_{j=1}^{n} t^u_{ij} \end{aligned} \tag{5}$$

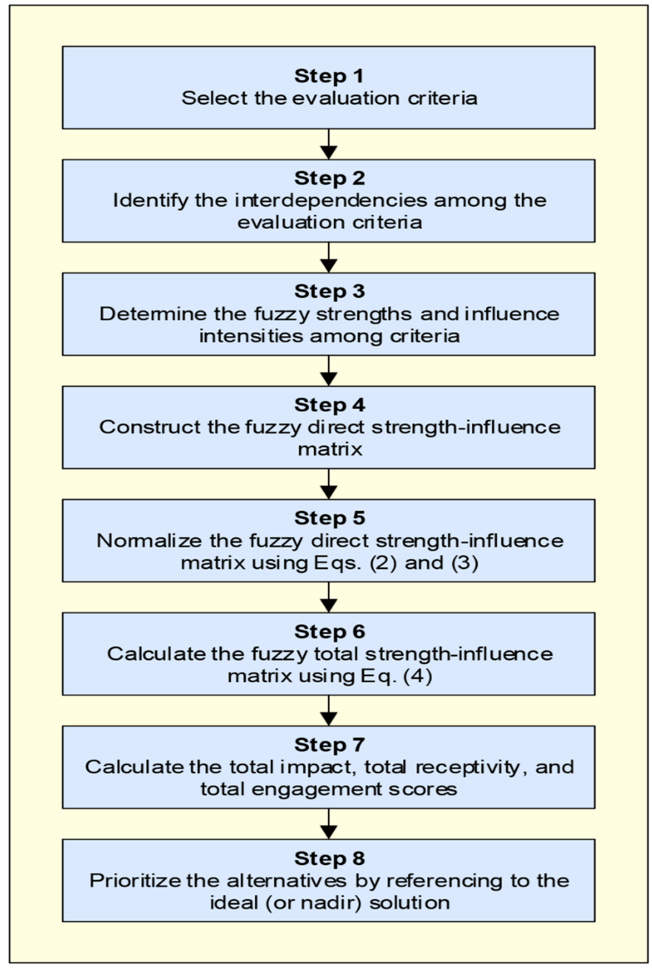


Fig. 3. Proposed fuzzy WINGS method.

$$\begin{aligned} &\widetilde{c}_j = \left[\left(c^l_j, c^m_j, c^u_j\right)\right] \\ &c^l_j = \sum_{i=1}^{n} t^l_{ij}, \quad c^m_j = \sum_{i=1}^{n} t^m_{ij}, \quad c^u_j = \sum_{i=1}^{n} t^u_{ij} \end{aligned} \tag{6}$$

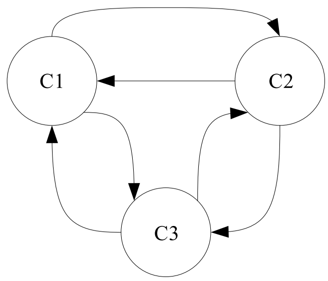
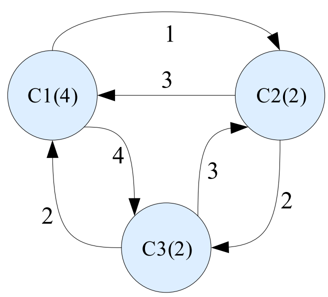
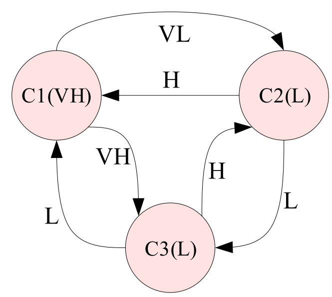
Next, the two indicators of total engagement ($\widetilde{r}_i + \widetilde{c}_i$) and role ($\widetilde{r}_i - \widetilde{c}_i$) are calculated by using Eq. (7) to defuzzify $\widetilde{r}_i$, $\widetilde{c}_i$, $\widetilde{r}_i + \widetilde{c}_i$, and $\widetilde{r}_i - \widetilde{c}_i$ (Zhou et al., 2018).

$$\begin{aligned} &r^{def}_i = \frac{r^l_i + 4 \times r^m_i + r^u_i}{6} \\ &c^{def}_i = \frac{c^l_i + 4 \times c^m_i + c^u_i}{6} \\ &(r_i + c_i)^{def} = \frac{\left(r^l_i + c^l_i\right) + 4 \times \left(r^m_i + c^m_i\right) + \left(r^u_i + c^u_i\right)}{6} \\ &(r_i - c_i)^{def} = \frac{\left(r^l_i - c^u_i\right) + 4 \times \left(r^m_i - c^m_i\right) + \left(r^u_i - c^l_i\right)}{6} \end{aligned} \tag{7}$$

Step 8: In this step, we use the Euclid method and the concepts of ideal (best) and nadir (worst) solutions as a reference point to plot the alternatives in a two-dimensional space with their $(r_i + c_i)^{def}$ scores on the horizontal dimension (x-axis) and their $(r_i - c_i)^{def}$ scores on the vertical dimension (y-axis), and rank the alternatives according to their Euclidean distances from the ideal (or nadir) solutions.

The steps involved in the proposed fuzzy WINGS method are illustrated in Fig. 3.

Table 3
A tabular presentation of WINGS and fuzzy WINGS solution for Example 1.

Step	WINGS	Fuzzy WINGS
1	C_1, C_2, C_3	
2		
3		
4	$M = \begin{bmatrix} 4 & 1 & 4 \\ 3 & 2 & 2 \\ 2 & 3 & 2 \end{bmatrix}$	$\widetilde{M} = \begin{bmatrix} (0.75,1,1) & (0,0.25,0.5) & (0.75,1,1) \\ (0.5,0.75,1) & (0.25,0.5,0.75) & (0.25,0.5,0.75) \\ (0.25,0.5,0.75) & (0.5,0.75,1) & (0.25,0.5,0.75) \end{bmatrix}$ $M^l = \begin{bmatrix} 0.75 & 0 & 0.75 \\ 0.5 & 0.25 & 0.25 \\ 0.25 & 0.5 & 0.25 \end{bmatrix}, M^m = \begin{bmatrix} 1 & 0.25 & 1 \\ 0.75 & 0.5 & 0.5 \\ 0.5 & 0.75 & 0.5 \end{bmatrix}, M^u = \begin{bmatrix} 1 & 0.5 & 1 \\ 1 & 0.75 & 0.75 \\ 0.75 & 1 & 0.75 \end{bmatrix}$
5	$N = \begin{bmatrix} 0.174 & 0.043 & 0.174 \\ 0.13 & 0.087 & 0.087 \\ 0.087 & 0.13 & 0.087 \end{bmatrix}$	$\widetilde{N} = \begin{bmatrix} (0.1,0.133,0.133) & (0,0.033,0.067) & (0.1,0.133,0.133) \\ (0.067,0.1,0.133) & (0.033,0.067,0.1) & (0.033,0.067,0.1) \\ (0.033,0.067,0.1) & (0.067,0.1,0.133) & (0.033,0.067,0.1) \end{bmatrix}$ $N^l = \begin{bmatrix} 0.1 & 0 & 0.1 \\ 0.067 & 0.033 & 0.033 \\ 0.033 & 0.067 & 0.033 \end{bmatrix}, N^m = \begin{bmatrix} 0.133 & 0.033 & 0.133 \\ 0.1 & 0.067 & 0.067 \\ 0.067 & 0.1 & 0.067 \end{bmatrix}, N^u = \begin{bmatrix} 0.133 & 0.067 & 0.133 \\ 0.133 & 0.1 & 0.1 \\ 0.1 & 0.133 & 0.1 \end{bmatrix}$
6	$T = \begin{bmatrix} 0.252 & 0.095 & 0.247 \\ 0.193 & 0.125 & 0.144 \\ 0.147 & 0.17 & 0.139 \end{bmatrix}$	$\widetilde{T} = \begin{bmatrix} (0.1159,0.1736,0.1932) & (0.008,0.0599,0.1168) & (0.1157,0.1716,0.1893) \\ (0.0788,0.1329,0.1942) & (0.0371,0.0869,0.1487) & (0.0435,0.097,0.1563) \\ (0.0435,0.0985,0.1613) & (0.0721,0.1208,0.1827) & (0.0411,0.0945,0.1552) \end{bmatrix}$ $T^l = \begin{bmatrix} 0.1159 & 0.008 & 0.1157 \\ 0.0788 & 0.0371 & 0.0435 \\ 0.0435 & 0.0721 & 0.0411 \end{bmatrix}, T^m = \begin{bmatrix} 0.1736 & 0.0599 & 0.1716 \\ 0.1329 & 0.0869 & 0.0970 \\ 0.0985 & 0.1208 & 0.0945 \end{bmatrix},$ $T^u = \begin{bmatrix} 0.1932 & 0.1168 & 0.1893 \\ 0.1942 & 0.1487 & 0.1563 \\ 0.1613 & 0.1827 & 0.1552 \end{bmatrix}$
7	$r_i = \begin{bmatrix} 0.594 \\ 0.462 \\ 0.456 \end{bmatrix}$ $c_j = [0.591 \quad 0.39 \quad 0.531]$	$\widetilde{r}_i = \begin{bmatrix} (0.2396,0.4051,0.4993) \\ (0.1594,0.3168,0.4992) \\ (0.1567,0.3138,0.4992) \end{bmatrix}, r_i^l = \begin{bmatrix} 0.2396 \\ 0.1594 \\ 0.1567 \end{bmatrix}, r_i^m = \begin{bmatrix} 0.4051 \\ 0.3168 \\ 0.3138 \end{bmatrix}, r_i^u = \begin{bmatrix} 0.4993 \\ 0.4992 \\ 0.4992 \end{bmatrix}$ $\widetilde{c}_j = [(0.2382,0.405,0.5487) \quad (0.1172,0.2676,0.4482) \quad (0.2003,0.3631,0.5008)]$ $c_j^l = [0.2382 \quad 0.1172 \quad 0.2003]$ $c_j^m = [0.405 \quad 0.2676 \quad 0.3631]$ $c_j^u = [0.5487 \quad 0.4482 \quad 0.5008]$
8	$r_i + c_i = \begin{bmatrix} 1.185 \\ 0.851 \\ 0.968 \end{bmatrix}, r_i - c_i = \begin{bmatrix} 0.003 \\ 0.072 \\ -0.075 \end{bmatrix}$ CriteriaRanking by $r_i c_i r_i + c_i r_i - c_i$ $C_1$1112 $C_2$2331	$\widetilde{r}_i + \widetilde{c}_i = \begin{bmatrix} (0.4778,0.8101,1.048) \\ (0.2766,0.5844,0.9474) \\ (0.357,0.6769,1) \end{bmatrix}, r_i^l + c_i^l = \begin{bmatrix} 0.4778 \\ 0.2766 \\ 0.357 \end{bmatrix}, r_i^m + c_i^m = \begin{bmatrix} 0.8101 \\ 0.5844 \\ 0.6769 \end{bmatrix}, r_i^u + c_i^u = \begin{bmatrix} 1.048 \\ 0.9474 \\ 1 \end{bmatrix}$ $\widetilde{r}_i - \widetilde{c}_i = \begin{bmatrix} (-0.3091,0.0001,0.2611) \\ (-0.2888,0.0492,0.382) \\ (-0.3441,-0.0493,0.2989) \end{bmatrix}, r_i^l - c_i^l = \begin{bmatrix} -0.3091 \\ -0.2888 \\ -0.3441 \end{bmatrix}, r_i^m - c_i^m = \begin{bmatrix} 0.0001 \\ 0.0492 \\ -0.0493 \end{bmatrix}, r_i^u - c_i^u = \begin{bmatrix} 0.2611 \\ 0.382 \\ 0.2989 \end{bmatrix}$ $(r_i)^{def} = \begin{bmatrix} 0.3932 \\ 0.321 \\ 0.3185 \end{bmatrix}, (c_i)^{def} = \begin{bmatrix} 0.4012 \\ 0.2726 \\ 0.3589 \end{bmatrix}, (r_i + c_i)^{def} = \begin{bmatrix} 0.7944 \\ 0.5936 \\ 0.6774 \end{bmatrix}, (r_i - c_i)^{def} = \begin{bmatrix} -0.0079 \\ 0.0483 \\ -0.0404 \end{bmatrix}$ CriteriaRanking by

(*continued on next page*)

Table 3 (*continued*)

Step	WINGS	Fuzzy WINGS
	$C_3$3223	$(r_i)^{def}(c_i)^{def}(r_i+c_i)^{def}(r_i-c_i)^{def}$
		$C_1$1112
		$C_2$2331
		$C_3$3223

3. Numerical examples

In this section, the reliability of the proposed fuzzy WINGS method is examined using two examples. Examples 1 and 2 are presented initially by Michnik (2013) to assess the WINGS method's efficiency.

3.1. Example 1

This example assumes three criteria influence each other. Table 3 presents the WINGS and fuzzy WINGS' solution procedures for this example.

Table 3 presents the rankings obtained from the WINGS and the proposed WINGS methods for all four r, c, $r+c$, and $r-c$.

3.2. Example 2

This example, originally presented as Example 2b by Michnik (2013), aims to rank the alternatives with intertwined criteria. In this example, two alternatives ($A_1$and A_2) are ranked using two criteria ($C_1$and C_2). It should be noted that criterion 2 influences criterion 1 in this example. In Table 4, the solving procedure of this example is presented using both methods.

Michnik (2013) has shown that the values of r, $r+c$, and $r-c$ are identical in problems where there are no interdependencies among the alternatives ($c = 0$). Therefore, Michnik (2013) suggests using the indicator r or $r+c$ to rank the alternatives in these problems. Similarly, as shown in Table 4, while ranking the alternatives with the fuzzy WINGS method, the c and $(c)^{def}$ values are identical for all alternatives. Hence, the rankings obtained from r, $r+c$, and $r-c$ are similar to each other.

4. Case study

In this section, we revisit an earlier application for evaluating advanced-technology projects at the KSC to demonstrate the applicability of the fuzzy WINGS approach proposed in this study. Readers should refer to Tavana (2003) for more details on the problem description. In this case study, the KSC management was considering ten advanced technology projects (i.e., Airlock, Babaloon, Centrifuge, Hubble, Nebula, Photovoltaic, Planet-finder, Solar, Tether, and Truss) with a total cost of $15,038,000. However, the budget cut had limited the spending to $6 million. The experts in the aerospace engineering division at the KSC were invited to revisit the earlier advanced technology project selection problem. They were asked to identify the interdependencies among the problem components, use the fuzzy linguistic terms presented in Table 2 to represent the strength of the factors, and suggest appropriate influence intensities for the components. The following evaluation process was used to select the most suitable projects with a total spending limit of $6 million.

Step 1: Six departments of safety (S), systems engineering (E), cost-savings (C), process-enhancement (P), reliability (R), and implementation (I) were selected to represent the selection criteria in the model and provide the necessary judgments for ranking the ten projects. Each department identified a set of sub-criteria to be used in the evaluation process. Table 5 presents the six criteria and 38 sub-criteria used in this study.

Steps 2 and 3: In these steps, the relationship between criteria, sub-criteria, and alternatives is determined. The hierarchical structure among the system components is depicted in Fig. 4. The strengths of the criteria and sub-criteria and their influence intensities are presented in this Figure. The influence intensities of the alternatives on the sub-criteria are presented in Table 6.

Step 4: In this step, the fuzzy direct strength-influence matrix is formed using the triangular fuzzy numbers presented in Table 2 and the structure in Fig. 4. The M^l, M^m, and M^u matrices used in this step are provided in an Excel file as **Online Resources**.

Step 5: In this step, the fuzzy direct strength-influence matrix is normalized using Eqs. (2) and (3). The N^l, N^m, and N^u matrices used in this step are provided in an Excel file as **Online Resources**.

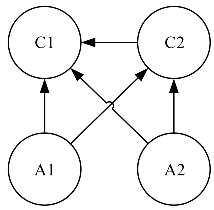
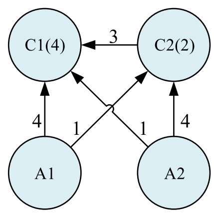
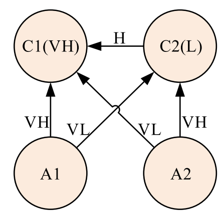
Step 6: In this step, the fuzzy total strength-influence matrix is calculated using Eq. (4). The T^l, T^m, and T^u matrices used in this step are provided in an Excel file as **Online Resources**.

Step 7: In this step, the total impact and total receptivity scores are calculated using Eqs. (5) and (6), respectively. Table 7 presents the total impact, receptivity, and engagement scores of the projects.

The WINGS method has a unique and exclusive feature that is not available in other techniques, including DEMATEL. A decision-maker in WINGS can consider both the strength and the intensity of the dependencies simultaneously. However, a significant challenge in WINGS is choosing a suitable evaluation measure among r, c, $r+c$, and $r-c$, for ranking the criteria, sub-criteria, or alternatives in the model. Michnik (2013) states the ranking results produced by r, $r+c$, and $r-c$ are identical because WINGS assumes no interdependencies among the alternative solutions in a decision problem. However, it is not clear which measure should be used in decision problems where the goal is to rank the intertwined criteria or sub-criteria. We eliminate this shortcoming in WINGS by integrating the Euclid model (Tavana, 2002, 2008, 2010, 2015) with WINGS for the first time. The integration of Euclid in WINGS allows for utilizing the concepts of ideal and nadir solutions borrowed from TOPSIS and the Euclidean distance measure into an integrated framework to rank the alternatives according to their $r+c$ and $r-c$ scores in a two-dimensional space. The Euclid method and its variations have been used for benchmarking global warming at Johnson Space Center (Tavana, 2008), European Union (EU) enlargement decisions by the European Commission to screen candidates for membership in the EU (Tavana et al., 2010), and The North Atlantic Treaty Organization (NATO) expansion decisions by NATO (Tavana et al., 2015). The alternatives are plotted in this two-dimensional space with their $r+c$ scores on the horizontal dimension (x-axis) and their $r-c$ scores on the vertical dimension (y-axis). We also plot the ideal solution (the most suitable solution) and the nadir solution (the least suitable solution) as the reference points in the solution space. The best alternative is the one that is closest to the ideal solution (or farthest from the nadir solution). Theoretically, the alternative rankings produced by the ideal or nadir solutions as reference points are identical.

Step 8: In this step, we identify the ideal and nadir solutions and plot the alternatives in a two-dimensional space with their $r+c$ and $r-c$ scores on the horizontal and vertical dimensions, respectively. Table 8 shows the ideal and nadir Euclidean distances for each alternative. As shown in this table, the $(r+c)^{def}$ results for both the ideal and nadir Euclidean distances are identical. Furthermore, the coordinates of the

Table 4
A tabular presentation of WINGS and fuzzy WINGS solution for Example 2b.

Step	WINGS	Fuzzy WINGS
1	Alternatives : A_1, A_2 Criteria : C_1, C_2	
2		
3		
4	$M = \begin{bmatrix} 4 & 0 & 0 & 0 \\ 3 & 2 & 0 & 0 \\ 4 & 1 & 0 & 0 \\ 1 & 4 & 0 & 0 \end{bmatrix}$	$M^l = \begin{bmatrix} 0.75 & 0 & 0 & 0 \\ 0.5 & 0.25 & 0 & 0 \\ 0.75 & 0 & 0 & 0 \\ 0 & 0.75 & 0 & 0 \end{bmatrix}, M^m = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0.75 & 0.5 & 0 & 0 \\ 1 & 0.25 & 0 & 0 \\ 0.25 & 1 & 0 & 0 \end{bmatrix},$ $M^u = \begin{bmatrix} 1 & 0.25 & 0.25 & 0.25 \\ 1 & 0.75 & 0.25 & 0.25 \\ 1 & 0.5 & 0.25 & 0.25 \\ 0.5 & 1 & 0.25 & 0.25 \end{bmatrix} \frac{1}{2}$
5	$N = \begin{bmatrix} 0.2105 & 0 & 0 & 0 \\ 0.1579 & 0.1053 & 0 & 0 \\ 0.2105 & 0.0526 & 0 & 0 \\ 0.0526 & 0.2105 & 0 & 0 \end{bmatrix}$	$N^l = \begin{bmatrix} 0.0938 & 0 & 0 & 0 \\ 0.0625 & 0.0313 & 0 & 0 \\ 0.0938 & 0 & 0 & 0 \\ 0 & 0.0938 & 0 & 0 \end{bmatrix}, N^m = \begin{bmatrix} 0.125 & 0 & 0 & 0 \\ 0.0938 & 0.0313 & 0 & 0 \\ 0.125 & 0 & 0 & 0 \\ 0.0313 & 0.0938 & 0 & 0 \end{bmatrix},$ $N^u = \begin{bmatrix} 0.125 & 0.0313 & 0.0313 & 0.0313 \\ 0.125 & 0.0938 & 0.0313 & 0.0313 \\ 0.125 & 0.0625 & 0.0313 & 0.0313 \\ 0.0625 & 0.125 & 0.0313 & 0.0313 \end{bmatrix}$
6	$T = \begin{bmatrix} 0.2667 & 0 & 0 & 0 \\ 0.2235 & 0.1176 & 0 & 0 \\ 0.2784 & 0.0588 & 0 & 0 \\ 0.1137 & 0.2353 & 0 & 0 \end{bmatrix}$	$T^l = \begin{bmatrix} 0.1034 & 0 & 0 & 0 \\ 0.0712 & 0.0323 & 0 & 0 \\ 0.1034 & 0 & 0 & 0 \\ 0.0067 & 0.0968 & 0 & 0 \end{bmatrix}, T^m = \begin{bmatrix} 0.1429 & 0 & 0 & 0 \\ 0.1143 & 0.0667 & 0 & 0 \\ 0.1464 & 0.0333 & 0 & 0 \\ 0.05 & 0.1333 & 0 & 0 \end{bmatrix},$ $T^u = \begin{bmatrix} 0.1584 & 0.0483 & 0.0402 & 0.0402 \\ 0.1689 & 0.1182 & 0.0429 & 0.0429 \\ 0.1637 & 0.0832 & 0.0416 & 0.0416 \\ 0.1018 & 0.1501 & 0.0417 & 0.0417 \end{bmatrix}$
7	$r_i = \begin{bmatrix} 0.2667 \\ 0.3412 \\ 0.3373 \\ 0.349 \end{bmatrix}$ $c_j = [0.8824 \quad 0.4118 \quad 0 \quad 0]$	$r_i^l = \begin{bmatrix} 0.1034 \\ 0.1034 \\ 0.1034 \\ 0.1034 \end{bmatrix}, r_i^m = \begin{bmatrix} 0.1429 \\ 0.181 \\ 0.1798 \\ 0.1833 \end{bmatrix}, r_i^u = \begin{bmatrix} 0.2871 \\ 0.3729 \\ 0.33 \\ 0.3353 \end{bmatrix}$ $c_j^l = [0.2848 \quad 0.129 \quad 0 \quad 0], c_j^l = [0.4536 \quad 0.2333 \quad 0 \quad 0],$ $c_j^u = [0.5928 \quad 0.3997 \quad 0.1664 \quad 0.1664]$
8	$rr + cr - c$	$(r)^{def}(r+c)^{def}(r-c)^{def}$Rank
	$A_1$0.33730.33730.3373	$A_1$0.19210.21980.16432
	$A_2$0.33730.33730.3373	$A_2$0.19540.22310.16761
	$A_2 > A_1$	$A_2 > A_1$

alternatives and their distance from the ideal and nadir solutions are depicted in Fig. 5. Fig. 6 and Table 9 present the final results. Given the \$6 million total spending budget, projects Photovoltaic, Hubble, and Babaloon with a total cost of \$5,635,000 are selected for implementation.

5. Conclusions

The missions of NASA are incredibly complicated and susceptible to catastrophic failure if equipment falters. For this reason, NASA carefully evaluates advanced technology projects to minimize failure and eliminate unexpected events. The evaluation of the advanced technology projects is generally difficult due to the lack of historical and precise

Table 5
The selection criteria and sub-criteria (Tavana, 2003).

Criteria	Sub-criteria	
Safety (S)	S-DSI	Eliminating the possibility of death or serious injury
	S-LOF	Eliminating the possibility of a loss of flight hardware, facility, or GSE
	S-PID	Eliminating the possibility of personal injury or flight hardware, facility, or GSE damage
	S-SVS	Eliminating the possibility of a serious violation of safety, health, or environmental federal/state
	S-DVS	Eliminating the possibility of a de minius violation of safety, health, or environmental
Systems Engineering (E)	E-LSP	Reducing or eliminating the possibility of launch slippage
	E-NTR	Supporting program for near-term requirements
	E-ONA	Eliminating the occurrence of nonsupport activities
	E-FAL	Reducing or eliminating a system failure
	E-OBS	Eliminating reliance on identified obsolete technology
Cost-savings (C)	C-LAB	Reducing or eliminating unnecessary labor dollars
	C-MAT	Reducing or eliminating unnecessary material dollars
	C-TSI	Utilizing time-sensitive implementation methodology
	C-MPC	Meeting the proposed cost
	C-MPS	Meeting the proposed schedule
	C-ROM	Reducing operations and maintenance costs
	C-CON	Meeting contractual obligations
Process Enhancement (P)	P-LPL	Reducing labor hours used on the launchpad
	P-LPT	Reducing launch and processing time
	P-LPA	Improving launchpad accessibility
	P-LPH	Reducing or eliminating hardware and materials expended on the launchpad
Reliability (R)	R-SFP	Eliminating critical single failure points (CSFPs)
	R-CFP	Reducing the possibility of failure propagation to other components or systems
	R-MTR	Improving the meantime to repair (MTTR)
	R-IFI	Improving Fault Identification and Fault Isolation (FI/FI)
	R-SIM	Providing for a simpler system
	R-AMT	Improving access for maintenance tasks
	R-TBF	Increasing mean time between failures (MTBFs)
	R-ETT	Reducing support equipment, special tools, and special training requirements
	R-COT	Providing for the use of standard commercial off-the-shelf (COTS) parts
	R-EQP	Providing for equipment interchangeability
Implementation (I)	I-MSA	Reducing or eliminating multisite applicability
	I-IMI	Reducing or eliminating the possibility of interference in the implementation
	I-FMC	Reducing or eliminating the possibility of flight-manifest changes
	I-MSC	Reducing or eliminating the effects on multisystem configuration systems
	I-EOH	Reducing or eliminating the possibility of equipment and occupational hazards
	I-SSR	Reducing or eliminating site-specific restrictions
	I-TCH	Meeting new technology considerations

performance data on unproven and untested new technologies in outer space. MCDM methods and approaches are often used to evaluate space programs and new technologies, according to expert opinions. However, conventional MCDM models often ignore the interdependencies and uncertainties in the evaluation process. We developed a fuzzy WINGS model to evaluate advanced technology projects at NASA. The proposed model uses ideographic causal maps to uncover the interdependencies among the evaluation criteria. Fuzzy logic is used in the model to represent uncertainties in the scientists' subjective judgments and opinions. The fuzzy WINGS model proposed in this study uncovered the interdependencies among the evaluation criteria and identified the direction and the intensity of the dependencies along with the strength of the evaluation criteria. Fuzzy judgments were used to handle uncertainties and lack of historical data on the performance of untested new technologies. We also used the concepts of *ideal* and *nadir* solutions and the Euclidean distance measure in WINGS for the first time to plot the alternatives in a two-dimensional space and rank them according to their $r+c$ and $r-c$ scores.

5.1. Managerial implications

This study presents a new and novel fuzzy WINGS method integrated with Euclid to solve complex decision-making problems under uncertainty. The triangular fuzzy numbers are used here to quantify the linguistic variables in WINGS because of their simplicity in both concept and computation. Among the various types of fuzzy numbers, the triangular fuzzy numbers are used most often to characterize linguistic information in practical applications because of their simplicity and ease of use. The WINGS method can uniquely consider both the strength and the intensity of the dependencies simultaneously. Other competing methods such as DEMATEL cannot capture the strength and the intensity of the dependencies simultaneously. In addition, the ability to easily capture and graphically depict complex interwind relationships in problems with hierarchical structures along with user-friendliness and low computational complexities and efforts are among the attractive features of this integrated framework. Furthermore, the integration of the Euclid model and the concepts of the *ideal* and *nadir* solutions allows the decision-makers to graphically see and compare each alternative in relation to the *ideal* and *nadir* solutions for ranking purposes according to their Euclidean distance measures. The integrated fuzzy WINGS method proposed in this study is simple and yet powerful. It graphically depicts the alternative solutions in a two-dimensional solution space for visual inspection. It is flexible because it does not limit the number of alternatives, criteria, sub-criteria, or hierarchical levels in decision problems. It also promotes participation because problem decomposition requires input from different levels of management in the organization. It is comprehensive because it simultaneously considers both the strength and the intensity of the dependencies in decision problems. Finally, managers often complain that analytical methods overlook subjective judgments. Subjective judgments are an essential aspect of the proposed framework.

5.2. Limitations and future research directions

In this paper, the triangular fuzzy numbers were used because of their simplicity and ease of use in real-life applications. However, other types of fuzzy numbers, including trapezoidal or type-2 fuzzy numbers, among others, could be used in the proposed integrated framework depending on their suitability and respective membership functions. In addition, while the proposed model was compared with two examples presented by Michnik (2013), the researchers are encouraged to compare this method with other MCDM methods, such as ANP, DEMATEL, and VIKOR. We also encourage researchers to conduct more studies on the simultaneous consideration of the strength and the intensity of the dependencies in MCDM models. Using the structured framework proposed in this study does not imply a deterministic approach to complex project evaluation at NASA or any other organization. While the proposed method helps decision-makers crystallize their thoughts and organize their judgments, it should be used with care. The effectiveness of any MCDM model depends on the ability of the

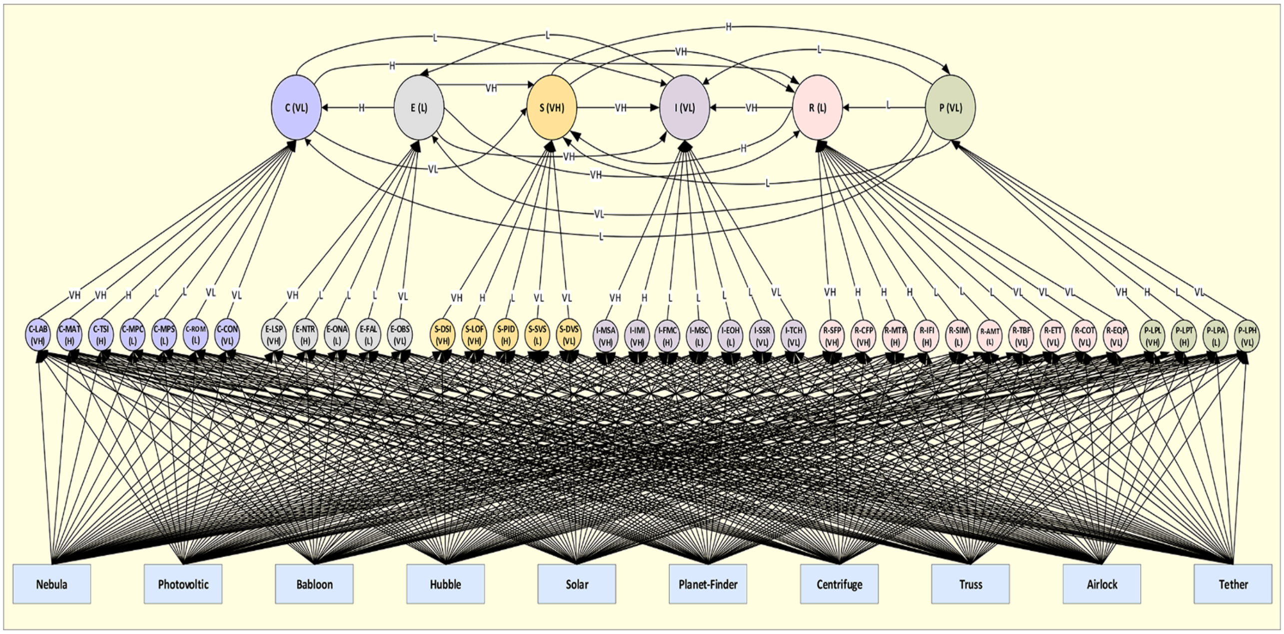


Fig. 4. Hierarchical structure between criteria, sub-criteria, and alternatives.

Table 6
The influence intensity of alternatives on sub-criteria.

	S-DSI	S-LOF	S-PID	S-SVS	S-DVS	E-LSP	E-NTR	E-ONA	E-FAL	E-OBS	C-LAB	C-MAT	C-TSI
Airlock	L	VH	H	VH	L	NO	H	NO	NO	VH	L	VH	VH
Babaloon	VH	H	VH	VL	L	H	H	L	VH	NO	L	H	VH
Centrifuge	VH	VH	VH	L	VH	VL	NO	L	NO	NO	H	VH	VH
Hubble	VH	L	VH	H	H	VL	H	L	H	VL	H	H	VH
Nebula	VH	VH	H	VH	H	H	VH	NO	L	NO	H	H	VH
Photovoltaic	H	H	VL	VH	VH	H	VH	VL	VH	VL	L	H	VH
Planet-Finder	VL	H	H	VH	VH	H	NO	VH	NO	NO	L	VH	VH
Solar	H	H	H	H	VH	L	NO	L	VH	NO	H	H	VH
Tether	L	H	VH	H	VL	VL	NO	L	VH	NO	L	L	VH
Truss	H	VH	H	VH	VH	VL	NO	VH	NO	NO	H	H	VH
Ideal	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH
Nadir	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL

	C-MPC	C-MPS	C-ROM	C-CON	P-LPL	P-LPT	P-LPA	P-LPH	R-SFP	R-CFP	R-MTR	R-IFI	R-SIM
Airlock	H	H	H	VH	H	VL	L	VH	VH	NO	H	NO	H
Babaloon	L	H	VH	VH	VL	L	VL	VH	NO	VH	VH	VH	NO
Centrifuge	H	H	H	VH	VL	VL	L	VL	H	VL	H	VH	VL
Hubble	H	H	H	H	VL	VH	VL	VL	VH	VH	H	H	VH
Nebula	H	H	VL	L	VL	H	VL	L	VH	VH	H	H	VH
Photovoltaic	H	H	H	VH	H	VH	VL	L	NO	H	VH	H	H
Planet-Finder	H	H	VL	VH	L	H	VH	VL	NO	H	H	H	NO
Solar	H	H	VL	VH	VL	VH	VL	VL	NO	VH	L	H	H
Tether	VL	H	H	VH	L	H	VL	VL	NO	NO	L	NO	H
Truss	L	H	H	H	VL	L	VL	VL	NO	NO	H	H	H
Ideal	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH
Nadir	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL

	R-AMT	R-TBF	R-ETT	R-COT	R-EQP	I-MSA	I-IMI	I-FMC	I-MSC	I-EOH	I-SSR	I-TCH	R-AMT
Airlock	H	NO	H	H	VH	H	H	H	H	L	H	VL	H
Babaloon	VH	NO	VH	VH	VH	VH	H	H	VH	H	H	VL	VH
Centrifuge	NO	H	H	VL	VH	H	VH	L	VH	H	H	VL	NO
Hubble	H	H	NO	VH	VH	NO	VH	VH	VH	VH	VH	NO	H
Nebula	VH	L	H	VL	NO	NO	VH	VH	VH	VH	VH	NO	VH
Photovoltaic	H	L	H	VL	H	VH	VH	VH	VH	H	VH	L	H
Planet-Finder	H	L	H	H	VL	H	L	L	VH	H	H	VL	H
Solar	VH	H	H	L	VH	VH	VL	VL	H	H	L	NO	VH
Tether	H	VH	H	H	NO	VH	VH	VH	H	VH	H	L	H
Truss	NO	H	NO	VH	H	VH	VH	VH	H	VH	H	VL	NO
Ideal	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH
Nadir	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL

Table 7
Total impact, receptivity, and engagement scores of the projects.

Projects	Total impact			Total receptivity			Total engagement			$(r_i + c_i)^{def}$	$(r_i - c_i)^{def}$
	r_i^l	r_i^m	r_i^u	c_i^l	c_i^m	c_i^u	$r_i^l + c_i^l$	$r_i^m + c_i^m$	$r_i^u + c_i^u$		
Airlock	0.0147	0.0220	0.0332	0	0	0.0131	0.0147	0.0220	0.0463	0.0248	0.0180
Babaloon	0.0163	0.0241	0.0337	0	0	0.0131	0.0163	0.0241	0.0468	0.0265	0.0195
Centrifuge	0.0135	0.0213	0.0321	0	0	0.0131	0.0135	0.0213	0.0451	0.0240	0.0174
Hubble	0.0165	0.0245	0.0346	0	0	0.0131	0.0165	0.0245	0.0477	0.0270	0.0199
Nebula	0.0156	0.0231	0.0332	0	0	0.0131	0.0156	0.0231	0.0463	0.0257	0.0188
Photovoltaic	0.0167	0.0252	0.0356	0	0	0.0131	0.0167	0.0252	0.0486	0.0277	0.0206
Planet-Finder	0.0135	0.0211	0.0325	0	0	0.0131	0.0135	0.0211	0.0456	0.0239	0.0173
Solar	0.0137	0.0215	0.0328	0	0	0.0131	0.0137	0.0215	0.0458	0.0243	0.0176
Tether	0.0128	0.0202	0.0314	0	0	0.0131	0.0128	0.0202	0.0444	0.0230	0.0165
Truss	0.0137	0.0209	0.0319	0	0	0.0131	0.0137	0.0209	0.0449	0.0237	0.0170
Ideal	0.0261	0.0348	0.0395	0	0	0.0131	0.0261	0.0348	0.0526	0.0363	0.0319
Nadir	0	0.0087	0.0219	0	0	0.0131	0	0.0087	0.0349	0.0116	0.0073

Table 8
A tabular presentation of the project rankings according to the ideal and nadir reference points.

Projects	$(r_i + c_i)^{def}$	$(r_i - c_i)^{def}$	Ideal Euclidean Distance	Nadir Euclidean Distance	Rank		
					Ideal	Nadir	$(r_i + c_i)^{def}$
Photovoltaic	0.0277	0.0206	0.0112	0.0247	1	1	1
Hubble	0.0270	0.0199	0.0121	0.0236	2	2	2
Babaloon	0.0265	0.0195	0.0127	0.0228	3	3	3
Nebula	0.0257	0.0188	0.0138	0.0216	4	4	4
Airlock	0.0248	0.0180	0.0150	0.0201	5	5	5
Solar	0.0243	0.0176	0.0156	0.0194	6	6	6
Centrifuge	0.0240	0.0174	0.0160	0.0189	7	7	7
Planet-Finder	0.0239	0.0173	0.0162	0.0188	8	8	8
Truss	0.0237	0.0170	0.0165	0.0183	9	9	9
Tether	0.0230	0.0165	0.0174	0.0173	10	10	10

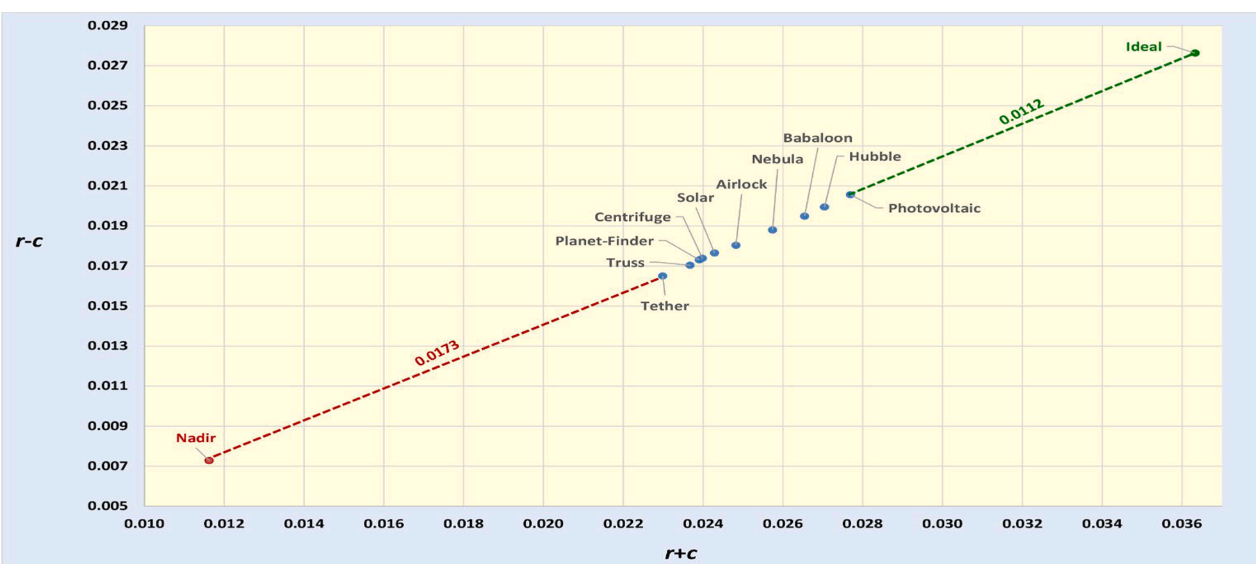


Fig. 5. A graphical presentation of the project rankings according to the ideal and nadir reference points.

decision-makers to provide sound judgments. As with any MCDM model, the decision-makers must be aware of the limitations of subjective judgments and estimates.

CRediT authorship contribution statement

Madjid Tavana: Conceptualization, Methodology, Investigation, Formal analysis, Visualization, Supervision, Validation. **Hossein Mousavi:** Formal analysis, Data curation, Validation. **Arash Khalili Nasr:** Formal analysis, Data curation, Validation. **Hassan Mina:** Conceptualization, Methodology, Formal analysis, Validation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

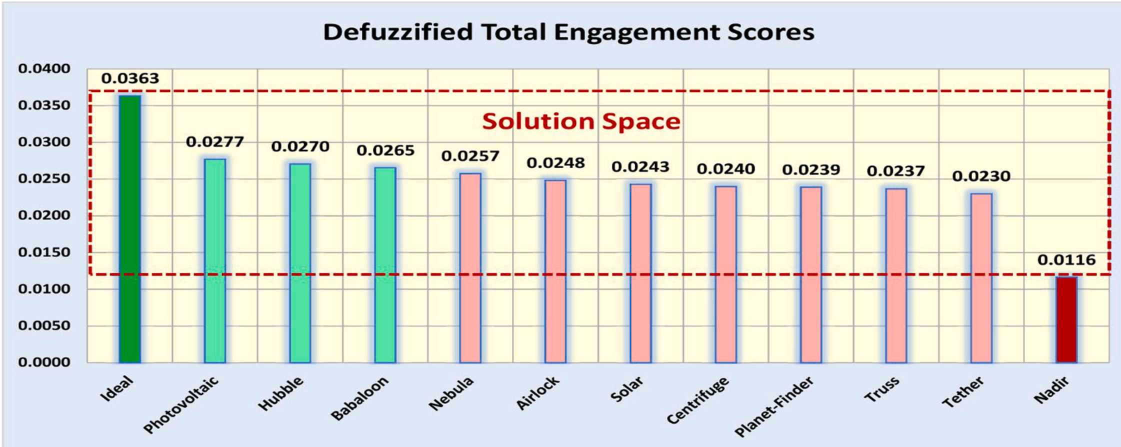


Fig. 6. The final case study results.

Table 9
Final results.

Project	Rank	Cost	Cumulative cost	Selected project
Photovoltaic	1	$1,908,000	$1,908,000	Yes
Hubble	2	$1,778,000	$3,686,000	Yes
Babaloon	3	$1,949,000	$5,635,000	Yes
Nebula	4	$1,348,000	$6,983,000	No
Airlock	5	$1,515,000	$8,498,000	No
Solar	6	$1,176,000	$9,674,000	No
Centrifuge	7	$1,790,000	$11,464,000	No
Planet-Finder	8	$1,266,000	$12,730,000	No
Truss	9	$1,347,000	$14,077,000	No
Tether	10	$961,000	$15,038,000	No

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Appendix A. Supplementary data

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