ISSN: 0273-1177
Volume 49,
Issue 4,
15 February 2012

ADVANCES IN SPACE RESEARCH

ELSEVIER

Available online at www.sciencedirect.com

SciVerse ScienceDirect

Advances in Space Research 49 (2012) 629–647

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

www.elsevier.com/locate/asr

Applying fuzzy bi-dimensional scenario-based model to the assessment of Mars mission architecture scenarios

Madjid Tavana [a,*], Faramak Zandi [b]

[a] *Information Systems and Decision Sciences, Lindback Distinguished Chair of Information Systems, La Salle University, Philadelphia, PA 19141, USA*

[b] *Information Systems and Decision Sciences, La Salle University, Philadelphia, PA 19141, USA*

Received 25 January 2011; received in revised form 9 November 2011; accepted 12 November 2011
Available online 22 November 2011

Abstract

Sending man to Mars has been a long-held dream of humankind. NASA plans human planetary explorations using approaches that are technically feasible, have reasonable risks and have relatively low costs. This study presents a novel Multi-Attribute Decision Making (MADM) model for evaluating a range of potential mission scenarios for the human exploration of Mars. The three alternatives identified by the Mission Operations Directorate (MOD) at the Johnson Space Center (JSC) include *split mission*, *combo lander* and *dual scenarios*. The proposed framework subsumes the following key methods: first, the conjunction method is used to minimize the number of alternative mission scenarios; second, the Fuzzy Risk Failure Mode and Effects Analysis (RFMEA) is used to analyze the potential failure of the alternative scenarios; third, the fuzzy group Real Option Analysis (ROA) is used to estimate the expected costs and benefits of the alternative scenarios; and fourth, the fuzzy group permutation approach is used to select the optimal mission scenario. We present the results of a case study at NASA's Johnson Space center to demonstrate: (1) the complexity of mission scenario selection involving subjective and objective judgments provided by multiple space exploration experts; and (2) a systematic and structured method for aggregating quantitative and qualitative data concerning a large number of competing and conflicting mission events.

Keywords: Mars mission; NASA; Fuzzy Risk Failure Mode and Effects Analysis; Real Option Analysis; Group permutation method; Conjunction method

1. Introduction

In an article entitled "Can we get to Mars?" published in Collier's Magazine in 1954, von Braun and Ryan write "No one can know what humans will find when they land on Mars – all that can be said with certainty is this: the trip can be made and will be made … someday" (von Braun and Ryan, 1954). The human exploration of Mars will be a complex undertaking. A three-year trip to Mars exponentially increases the risks of space travel. NASA is planning for the human exploration of MARS with an acceptable level of risk consistent with other manned operations. Space exploration risks cannot be completely eliminated. Therefore, an acceptable level of risks, costs and benefits must be established for the human exploration of Mars. The crew will travel to and from Mars on a relatively fast transit of approximately 6 months and will spend long periods of time (520–580 days) on the surface. Shorter transit times reduce: (1) the time spent by the crew in zero gravity; (2) the exposure to galactic cosmic radiation; and (3) the probability of encountering solar particle incidents. The Mission Operations Directorate (MOD) at the Johnson Space Center (JSC) is considering the following three alternative mission scenarios for the human exploration of Mars: *split mission*, *combo lander* and *dual scenarios*. The three alternative architectures were identified from previous architecture studies and anticipated capabilities. A detailed description of the three scenarios is presented in Table 1.

* Corresponding author. Tel.: +1 215 951 1129; fax: +1 267 295 2854.
E-mail addresses: tavana@lasalle.edu (M. Tavana), zandi@lasalle.edu (F. Zandi).
URL: http://www.lasalle.edu/~tavana (M. Tavana).

0273-1177/$36.00 © 2011 COSPAR. Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.asr.2011.11.019

Table 1
The alternative mission scenarios for the human exploration of Mars.

Mission scenario	Description
Split Mission (A_1)	In this scenario, the mission is split into two steps: pre-deployment of mission assets to the planet surface, followed by the mission crew. During the assets deployment step, the Return Habitat/Ascent Vehicle will be sent to Mars. Upon arriving in a Mars orbit, the Return Habitat will stay in the orbit while the Ascent Vehicle lands on Mars and starts producing fuel. After the mission equipment is configured and tested to be viable, the Transit Habitat/Surface Habitat vehicle will be sent into Earth orbit. The crew will be transferred to the Transit Habitat/Surface Habitat vehicle at a later date. Next, the Transit Habitat/Surface Habitat vehicle and the crew will be sent to Mars to land near the Ascent Vehicle. After the completion of surface exploration, the Ascent Vehicle will be used to transfer the crew to the Return Habitat vehicle, which will be orbiting Mars. The Return Habitat vehicle will be used to return the crew to Earth
Combo Lander (A_2)	In this scenario, the mission assets will travel to and from Mars with the crew. Initially, the Transit Habitat/Surface Habitat/Ascent Vehicle will be launched into Earth's orbit. The crew will be transferred to the Transit Habitat/Surface Habitat/Ascent Vehicle in Earth's orbit at a later date. Next, the Transit Habitat/Surface Habitat/Ascent Vehicle will be sent to Mars with the crew. Upon arriving in a Mars's orbit, the Transit Habitat vehicle will separate and remain in Mars's orbit while the crew uses the Surface Habitat/Ascent Vehicle to land on Mars. After the completion of surface exploration, the Ascent Vehicle will be used to transfer the crew to the Transit Habitat vehicle, which will return the crew to Earth
Dual (A_3)	In this scenario, the Transit Habitat/Surface Habitat/Ascent Vehicle/Descent Vehicle will be launched into Earth's orbit. The crew will be transferred to the Transit Habitat/Surface Habitat/Ascent Vehicle/Descent Vehicle at a later date. Next, the Transit Habitat/Surface Habitat/Ascent Vehicle/Descent Vehicle will be sent to Mars with the crew. Upon arriving in Mars's orbit, the Transit Habitat vehicle will stay in the orbit, the Surface Habitat vehicle will land on Mars unmanned, and the crew will use the Ascent/Descent Vehicle to land on Mars near the Surface Habitat. After the completion of surface exploration, the Ascent Vehicle will be separated and used to transfer the crew to the Transit Habitat vehicle, which will return the crew to Earth

Mars has held the imagination of humanity for millennia, yet only recently has it become feasible to send explorers to Mars and extend our presence on the Red Planet. The choice of trajectory type, mission duration, vehicle options, and other concerns together constitute the architecture. For half-century, NASA has been evaluating different human Mars exploration architectures and strategies internally and with international space agencies. Scientists and engineers have proposed a range of mission scenarios as means to realize human exploration of Mars (von Braun, 1953; Himmel et al., 1961; Mueller, 1970; Donahue, 1995; Zubrin and Wagner, 1996; Mankins, 2002; Landau and Longuski, 2009; Cooper et al., 2010; Moore, 2010; Murphy et al., 2010). However, despite a variety of comparative analyses, there is still no definitive answer to how we shall explore the Red Planet (Lee and Wilson, 1967; Braun and Blersch, 1991; Walberg, 1993; Donahue and Cupples, 2001; Landau and Longuski, 2009).

The logistics of a manned mission to Mars are complex to say the least. Before setting out into the solar system on our way to the Red Planet, there are a seemingly endless number of concerns to take into consideration. These concerns range from multiple mission scenarios, to different Earth and Mars orbit and surface operations, to crew safety, and much more (Reichert, 2001; Mendell, 2005; Salotti, 2011). Mission planners need to balance the risks, costs and benefits of human exploration of Mars. A comprehensive and structured methodology is needed to select candidate mission scenario with the minimum risks and costs, and maximum benefits. This selection methodology must involve multiple experts, a wide range of quantitative and qualitative inputs, and a mixture of objective and subjective judgments (Tavana, 2007; Tavana et al., 2007).

The main risks associated with the human exploration of Mars are the spacecraft hardware, software and liveware. Mendell and Heydorn (2004) have defined life support, power generation, propulsion, guidance and communications as mission critical systems. Mendell (2005) further characterized uncertainty in crew health and performance, lack of experience with mission operations, and system maintenance and failure as additional areas of concern in a manned Mars mission. Mendell (2005) has also suggested that mission planners must take into full consideration a comprehensive architecture when designing a manned mission to Mars because complex systems, like spacecraft, are known to fail in ways not predictable. In the event of the unexpected, there will be no quick return to, or supplementary supply from, Earth due to the nature of the flight trajectory.

Early costs for a manned mission to Mars ranged from a low of \$20 billion (Zubrin and Wagner, 1996) to a high of \$450 billion (NASA, 1989). The higher estimate included use of the moon as a launch point. The wide range persists in more modern estimates of the cost Ehlmann et al. (2005) estimated the cost to be between \$30 billion to \$300 billion. Hunt and vanPelt (2004) have categorized the following required expenditures for the human exploration of Mars: flight equipment development and production; ground infrastructure development and production; flight and ground software development; operations costs and all system level costs, including those at space agency level.

Sadeh and Vlachos (1998) have identified the following benefits associated with the human exploration of Mars: (1) national prestige and leadership; (2) exploration and scientific knowledge; (3) economic growth and development (e.g., space commercialization and privatization); (4) enabling technologies and technological innovation; and (5) international cooperation. A manned Mars mission would direct the resources and infrastructure of NASA into high-technology research and development. The increased investment in high-technology would create new jobs and markets and improve the quality of life throughout the world.

We propose a Multi-Attribute Decision Making (MADM) model for minimizing risks and costs, and maximizing benefits associated with a range of manned Mars mission scenarios. The fuzzy permutation method is used to measure the level of concordance in preference order of multiple space exploration experts. Each possible ranking of the alternative architectures is compared with all other rankings and the best ranking is chosen according to the concept of concordance and discordance in outranking. The fuzzy permutation method is a useful approach owing its simplicity and flexibility to cardinal and ordinal rankings (Chen and Wang, 2009; Hwang and Yoon, 1981). To the best of our knowledge, this study presents the first application of the fuzzy permutation method in space and planetary exploration.

This paper is organized into six sections. The next section presents a literature review on scenario planning, MADM, Risk Failure Mode and Effects Analysis (RFMEA), and Real Option Analysis (ROA). In Section 3, we present the mathematical notations and definitions used in our method. In section 4, we illustrate the details of the proposed method. In section 5, we present the results of a case study at NASA's Johnson Space center. In section 6, we sum up with our conclusions and future research directions.

2. Literature review

Scenario development in strategic decision making facilitates strategy formulation and evaluation and improves understanding of the uncertainties. Scenario planning involves thinking about a wide range of future outcomes and addresses three issues (O'Brien, 2004):

- The synthesis of information about what is vital for an organization, a necessary groundwork for understanding future uncertainties,
- The development of a consistent and plausible set of possible futures or scenarios through the use of a structured framework, and
- The evaluation of the implications of these scenarios for the organization.

Scenarios are generally useful for encouraging systematic planning in situations of uncertainty (van Notten et al., 2003) or for revealing a range of dynamic processes that lead to alternative courses of action (Rotmans et al., 2000). Over the years, a variety of scenario development methods have been proposed in the literature. One key characteristic of such methods is that they seek to develop multiple scenarios, usually between two and four. Schwartz (1996), for example, observes "Two [scenarios] may not capture reality, so you often use three. On rare occasions you might consider four." Another common characteristic of these methods is the level of participation recommended for the development of the scenarios, usually a group of Decision Makers (DMs) rather than an individual DM. A differentiating characteristic between the methods is the extent to which probabilities and quantification are integrated into the process (O'Brien, 2004).

In this study, we use a novel MADM model to evaluate three mission scenarios for the human exploration of Mars.Scenarios help policy-makers and scientists make better sense of changes in their external environment, spot early warning signals and refine perceptions of existing or emerging problems and corresponding problem-solving strategies (Bradfield et al., 2005). Over the recent decades, scenario planning has formed a growing area of interest among the space exploration experts facing strategic decisions with uncertain future outcomes (Huntley et al., 2010; Kotnour and Bollo, 2011; Salotti, 2011).

A number of decision methodologies in the group decision-making context have been presented in the MADM literature. A comprehensive survey can be found in Hwang and Lin (1987). Iz and Gardiner (1993) review formal group decision-making models and describe some examples of conceptual frameworks and actual implementations of group decision-making models. A comprehensive collection of research devoted to synthesis and analysis of group support frameworks and procedures can be found in Jessup and Valacich (1993). When facing such multiple events, the literature and research show that the following difficulties may be encountered:

(a) DMs often use verbal expressions and linguistic variables for subjective judgments that lead to ambiguity (Poyhonen et al., 1997). Furthermore, the subjective assessment process is intrinsically imprecise and may involve two types of judgments: comparative judgment and absolute judgment (Saaty, 2006).
(b) DMs often provide imprecise or vague information due to lack of expertise, unavailability of data or time constraint (Kim and Ahn, 1999).
(c) Meaningful and robust aggregation of subjective and objective judgments affects the evaluation process (Valls and Torra, 2000).

A decision may not be appropriately made without fully considering its context and all criteria (defined as events in this study) in a MADM (Belton and Stewart, 2002; Yang and Xu, 2002). Recently, MADM researchers have focused on models to integrate the intuitive preferences of multiple DMs into structured and analytical frameworks (Bailey et al., 2003; Costa et al., 2003; Hsieh et al., 2004; Liesiö et al., 2007; Tavana, 2004,, 2006). We built a MADM model to evaluate three alternative mission scenarios according to 40 possible events. The events used in this study were categorized into seven groups. Each group of events was associated with a specific mission phase in the Mars architecture designed for this study. MADM requires the determination of weights that reflect the relative importance of various events. Several approaches such as point allocation, paired comparisons, trade-off analysis and regression estimates could be used to specify these weights (Kleindorfer et al., 1993). In this study, the importance weight of the mission phases and the importance weight of the events within each mission phase were determined based on the pairwise comparisons and eigenvalue theory proposed by Saaty (2006).

Within the broad field of space and planetary applications, MADM has been used for design and development of automation systems in space (Lavagna and Ercoli Finzi, 2002); benchmarking technology assessment at NASA (Tavana, 2004,); space vehicle design (Arney et al., 2010); and human spaceflight mission planning (Tavana and Hatami-Marbini, 2011). The MADM model proposed in this study captures the DMs' beliefs concerning alternative Mars mission scenarios through a series of intuitive and analytical methods and integrates them with a meaningful and robust aggregation method. The conjunction method, fuzzy RFMEA, fuzzy ROA, and fuzzy group permutation approach are used to select the optimal Mars mission scenario.

In the conjunction method, the DM assigns maximum acceptable standard levels to all the events. In this method, if a scenario exceeds the maximum acceptable standard level on one event, then, it will be considered not acceptable, independent of the standard levels on the remaining events. If no scenario is acceptable, then, the DM may reduce the maximum acceptable standard levels for one or more events (Dawes, 1964; Simon, 1955). We use the conjunction method in our model to minimize the number of scenarios in the assessment process.

The FMEA was first developed as a formal design methodology in the 1960s from studies done by NASA and has been extensively used for examining potential failures in products, processes, designs and services by determining the risk priorities of the failure modes (Hu et al., 2009). The FMEA is a tool widely used in the aerospace industry to identify, prioritize and eliminate known potential failures and problems from systems before deployment (Stamatis, 1995). In its Safety Manual, NASA states that "The primary purpose of risk assessment is to identify and evaluate risks to help guide decision making and risk management regarding actions to ensure safety and mission success...Quantitative methods can be used to evaluate probabilities, consequences, and uncertainties, whenever possible. Qualitative methods characterize hazards, and failure modes and effects provide valuable input to the risk assessment" (NASA NPR 8715.3, 2011).

The traditional FMEA requires the risk factors like the likelihood, severity and detection of each failure mode to be evaluated. The multiplication of these values leads to what is known as the risk priority number (RPN). Carbone and Tippett (2004) have proposed an extension of the traditional FMEA called RFMEA that focuses on the most imminent risks, prioritize risk contingency planning, improve team participation in the risk management process and improve risk controls. In the RFMEA, the "failure mode" column is replaced with the "risk incident," the "occurrence" is named "likelihood," and the "severity" is named "impact" (Carbone and Tippett, 2004).

The RFMEA requires precise evaluation of the likelihood, impact and detection values. However, values of the risk factors in real-world problems are often imprecise or vague. In this study, we use fuzzy RFMEA to manage the imprecise or vague risk values and the complex, subjective and qualitative relationships among the failure modes. Compared with the traditional FMEA and its various extensions and fuzzy improvements, the fuzzy RFMEA used in this study has the following advantages:

- It is more practical because the relative importance among the risk factors' likelihood, impact and detection, is taken into consideration in the prioritization of the failure modes.
- It is more realistic because the risk factors and their relative importance weights are evaluated in linguistic terms rather than in precise numerical values.
- It fully prioritizes failure modes and distinguishes them from one another because different combinations of likelihood, impact and detection produce different FRPNs unless the relative weights among them are the same.
- It is easier to implement because there is no need to build any if–then rules which are costly and time-consuming.
- It is more flexible because the proposed fuzzy RFMEA is not limited to likelihood, impact and detection and additional risk factors can be incorporated into the fuzzy RPNs if necessary.

In addition to the risk assessment with fuzzy RFMEA, we capture the costs and benefits associated with the alternative mission scenarios through ROA. In recent years, several researchers have proposed methods for estimating the range of option values across a wide spectrum of future scenarios in MADM. The conventional MADM methods tend to be less effective in conveying the imprecision and vagueness characteristics. This has led to the development of fuzzy set theory. Starting from the pioneering publication of Zadeh (1965), fuzzy sets have been applied to many fields in which uncertainty plays a key role. Zadeh (1965) has proposed that the key elements in human thinking are not numbers but labels of fuzzy sets. Much knowledge in the real world is fuzzy rather than precise and fuzzy ROA can help DMs cope with the environmental uncertainties in capital investment assessment.

Carlsson and Fullér (2003) introduced a (heuristic) real option rule in a fuzzy setting, where the expected risks, costs and benefits were estimated by trapezoidal fuzzy numbers. Chen et al. (2007) developed a comprehensive but simple methodology to evaluate information technology investment in a nuclear power station based on fuzzy risk analysis and the real option approach. Frode (2007) used the conceptual real option framework of Dixit and Pindyck (1994) to estimate the value of investment opportunities in the Norwegian hydropower industry. Villani

(2008) combined two successful theories, namely real option and game theory, to value the investment opportunity and the value of flexibility as a real option while analyzing the competition with game theory. ROA has been used in space exploration research for designing space missions (Gray et al., 2005); purchasing a swarm of uninhabited air vehicles (Mikaelian et al., 2009), evaluating large and risky expenditures on long-lived capital investments (Koenig, 2009); and valuing a large-scale space solar power venture (Gilboa and Guo, 2011). In the next section we present the mathematical notations and definitions used in our model.

3. The mathematical notations and definitions

Let us introduce the following mathematical notations and definitions:

A_i	The ith mission scenario
n	The number of mission scenarios
p_j	The jth mission phase
m	The number of mission phases
c_h	The hth event
v_j	The number of events in the jth mission phase
s	The number of space exploration experts
$w_j(p)$	The importance weight of the jth mission phase
$w_h^j(c)$	The importance weight of the hth event in the jth mission phase
$C_{kl}(j)$	The concordance set that is a subset of all events in the jth mission phase
$D_{kl}(j)$	The discordance set that is a subset of all events in the jth mission phase
$\underline{T}$	The space exploration team
$m(b)$	The bth member of the space exploration team
$\tilde{a}_{ih}^1(m(b)_j)$	The fuzzy individual failure impact rating of the hth event on the ith mission scenario in the jth mission phase evaluated by the bth member of the space exploration team
$\tilde{a}_{ih}^2(m(b)_j)$	The fuzzy individual failure likelihood rating of the hth event on the ith mission scenario in the jth mission phase evaluated by the bth member of the space exploration team
$\tilde{a}_{ih}^3(m(b)_j)$	The fuzzy individual failure detection rating of the hth event on the ith mission scenario in the jth mission phase evaluated by the bth member of the space exploration team
$\tilde{a}_{ih}^{RPN}(j)$	The collective fuzzy risk priority number for the $i$thmission scenario on the hth event in the jth mission phase
$\tilde{\beta}_h^{RPN}(j)$	The fuzzy standard level of risk priority number for the hth event evaluated by the space exploration team members collectively in the jth mission phase
$A_{(i)}[r(j)]$	The assigned rank to the ith mission scenario with respect to the $j$thmission phase
$A_{(i)}[r]$	The assigned rank to the ith mission scenario with respect to all mission phases
$\tilde{s}_i[m(b)_f]$	The individual fuzzy expected benefits for the ith mission scenario evaluated by the bth member of the space exploration team
$\tilde{x}_i[m(b)_f]$	The individual fuzzy expected costs for the ith mission scenario evaluated by the bth member of the space exploration team
$\tilde{s}_i$	The collective fuzzy expected benefits for the ith mission scenario
$\tilde{x}_i$	The collective fuzzy expected costs for the ith mission scenario
$E(\tilde{s}_i)$	The expected value of the collective fuzzy expected benefits for the ith mission scenario
$E(\tilde{x}_i)$	The expected value of the collective fuzzy expected costs for the ith mission scenario
σ_i^2	The variance of the collective fuzzy expected benefits for the ith mission scenario
$n(d_{1i})$	The ith mission scenario cumulative normal probability for the d_{1i}
$n(d_{2i})$	The ith mission scenario cumulative normal probability for the d_{2i}
$\widetilde{ROV}_i$	The fuzzy real option value of the ith mission scenario
$\widetilde{R}^f(b)$	The individual fuzzy real option matrix of the mission scenarios evaluated by the bth member of the space exploration team
$\widetilde{R}^f$	The fuzzy collective real option matrix
$ROV(f)$	The real option value vector of the mission scenarios

4. The proposed method

The framework depicted in Fig. 1 is proposed to select the optimal mission scenario for the human exploration of Mars. In this framework, we evaluate each alternative mission scenario according to two dimensions: ROA dimension and RFMEA dimension. In the ROA dimension, we consider the costs and benefits associated with each mission scenario. In the RFMEA dimension, we consider the likelihood ,impact and detection of all potential failures associated with the mission scenarios.

As shown in Fig. 2, the proposed framework consists of several processes, steps and procedures modularized into three stages:

4.1. Stage 1. The development of the best order of the mission scenarios for the RFMEA dimension

In this stage, we use the fuzzy group permutation method to prioritize the mission scenarios according to the overall likelihood, impact and detection of their potential failures. This stage is divided into the following four processes:

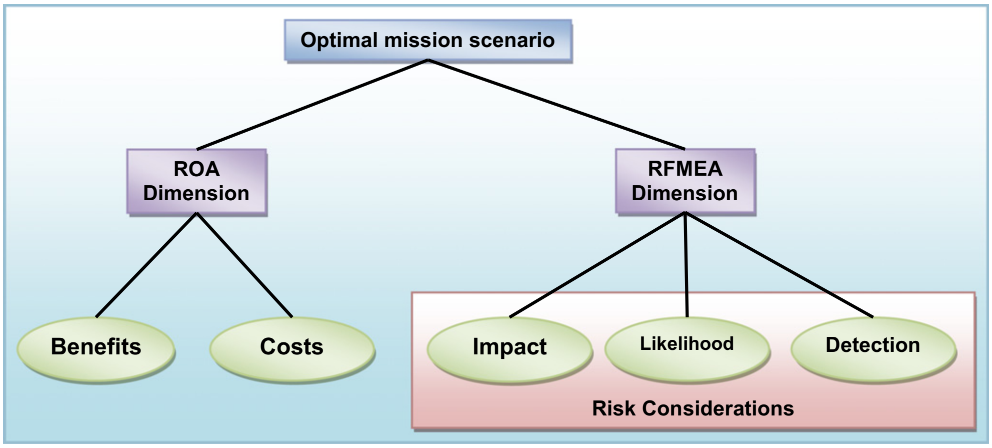

Fig. 1. The mission scenario selection framework.

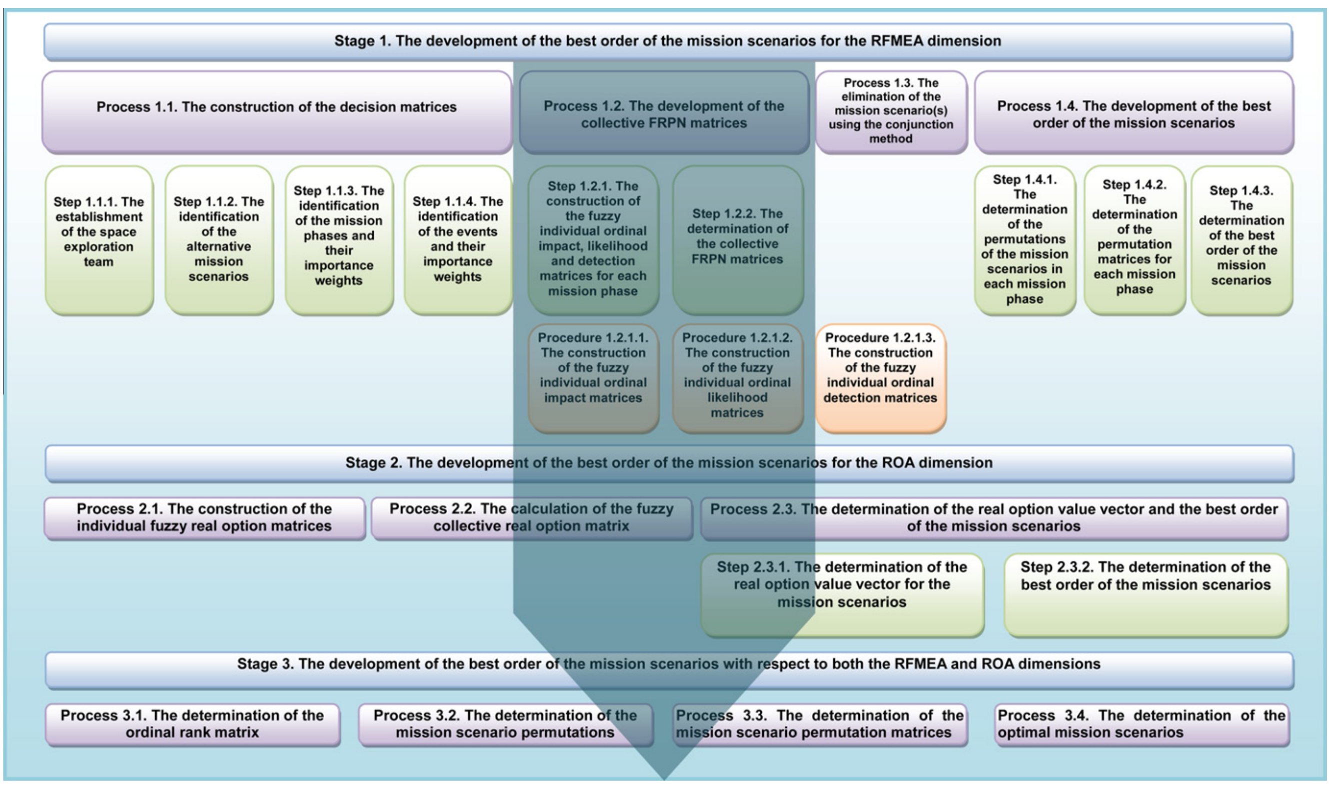

Fig. 2. The details of the proposed framework.

4.1.1. Process 1.1. The construction of the decision matrices

In this process, we construct a likelihood, impact and detection matrix of events-alternative mission scenarios for each mission phase. This process is comprised of four steps:

4.1.2. Step 1.1.1. The establishment of the space exploration team

In the first step, we establish a space exploration team. Let us assume that the members of the space exploration team are as follows:

$$\underline{T} = (m(1), m(2), \ldots, m(s)) \tag{1}$$

4.1.3. Step 1.1.2. The identification of the alternative mission scenarios

In the second step, the space exploration team identifies a set of viable mission scenarios based on previous architecture studies and anticipated capabilities. Let us assume that the team has identified n mission scenarios as follows:

$$\underline{A} = [A_1, A_2, \ldots, A_n] \tag{2}$$

We should note that we do not consider any constraints in this step of the framework. However, potential constraints could be treated as events in Step 1.1.4.

4.1.4. Step 1.1.3. The identification of the mission phases and their importance weights

In the third step, the space exploration team identifies the mission phases required for the human exploration of Mars along with their importance weights. The importance weights of the mission phases are determined based on the pairwise comparisons and eigenvalue theory proposed by Saaty (2006). Saaty (2006) has developed the eigenvalue method in order to synthesize a pairwise comparison matrix and to obtain a priority weight vector. The eigenvector provides the priority weights of the mission phases and the eigenvalue provides a measure of judgment consistency in pairwise comparisons. Let us consider the following mission phases: $x_1(p), x_2(p), \ldots, x_m(p)$ with the following importance weights:

$$\underline{W(p)} = (w_1(p), w_2(p), \ldots, w_m(p)) \tag{3}$$

4.1.5. Step 1.1.4. The identification of the events and their importance weights

In the fourth step, the space exploration team identifies a set of events for each mission phase. The importance weights of the events in each mission phase are determined based on the pairwise comparisons and eigenvalue theory described in Step 1.1.3. Let us consider the following events: $x_{1j}(c), x_{2j}(c), \ldots, x_{v_j j}(c)\, j = 1, 2, \ldots, m$; with the following importance weights:

$$\underline{W^j(c)} = \left(w_1^j(c), w_2^j(c), \ldots, w_{v_j}^j(c)\right) \tag{4}$$

4.1.6. Process 1.2. The development of the collective FRPN matrices

In this process, we use the following two steps to determine the collective FRPN matrices based on the RPN index proposed in the guide to the Project Management Body of Knowledge (PMBOK) (PMI, 2009).

4.1.7. Step 1.2.1. The construction of the fuzzy individual ordinal impact, likelihood and detection matrices for each mission phase

In this step, we use the following three procedures to calculate the individual FRPN matrices for each mission phase:

4.1.8. Procedure 1.2.1.1. The construction of the fuzzy individual ordinal impact matrices

According to the PMBOK Guide (2009) for qualitative risk analysis, the impact events are those events that their occurrence will result in the effect on scenario objectives (PMI, 2009). Each space exploration team member constructs a fuzzy individual ordinal impact matrix for the mission phase j using the information provided in Steps 1.1.2 and 1.1.4. Considering n mission scenarios, a 1 to n fuzzy number scale is used to represent the impact rating for the failure of an event and a mission scenario in the matrix $\left(1 \leqslant \tilde{a}_{ih}^1(m(b)_j) \leqslant n\right)$. This process is repeated m times and a fuzzy individual ordinal impact matrix is constructed for each mission phase as follows:

$$\widetilde{D}^1(m(b)_j) = \begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_n \end{array} \begin{array}{c} \begin{array}{cccc} x_{1j}(c) & x_{2j}(c) & \cdots & x_{v_j j}(c) \end{array} \\ \begin{bmatrix} \tilde{a}_{11}^1(m(b)_j) & \tilde{a}_{12}^1(m(b)_j) & \cdots & \tilde{a}_{1v_j}^1(m(b)_j) \\ \tilde{a}_{21}^1(m(b)_j) & \tilde{a}_{22}^1(m(b)_j) & \cdots & \tilde{a}_{2v_j}^1(m(b)_j) \\ \vdots & \vdots & \cdots & \vdots \\ \tilde{a}_{n1}^1(m(b)_j) & \tilde{a}_{n2}^1(m(b)_j) & \cdots & \tilde{a}_{nv_j}^1(m(b)_j) \end{bmatrix} \end{array}; \tag{5}$$

where the trapezoidal fuzzy number $\tilde{a}_{ih}^1(m(b)_j)$ is defined with a tolerance interval $[c, d]$, left width α and right width β if its membership function presented in Fig. 3 is shown with the notation $A = (c, d, \alpha, \beta)$ and has the following form *i*.:

$$\begin{cases} 1 - \frac{c-t}{\alpha} & \text{if } c - \alpha \leqslant t \leqslant c \\ 1 & if\ c \leqslant t \leqslant d \\ 1 - \frac{t-d}{\beta} & \text{if } d \leqslant t \leqslant d + \beta \\ 0 & \text{otherwise} \end{cases}$$

Among the various types of fuzzy numbers, triangular and trapezoidal fuzzy numbers are most important. We chose trapezoidal fuzzy numbers for this study because they are used most often for characterizing uncertainty in practical applications (Klir and Yuan, 1995; Yeh and Deng, 2004).

4.1.9. Procedure 1.2.1.2. The construction of the fuzzy individual ordinal likelihood matrices

According to the PMBOK Guide (2009) for qualitative risk analysis, the risk probability is the likelihood that a risk will occur in the project. Each space exploration team member constructs a fuzzy individual ordinal likelihood matrix for the mission phase j using the information provided in Steps 1.1.2 and 1.1.4. Considering$n$ mission scenarios, a 1 to n fuzzy number scale is used to represent the likelihood rating for the failure of an event and a mission scenario in the matrix $\left(1 \leqslant \tilde{a}_{ih}^2(m(b)_j) \leqslant n\right)$. This process is repeated m times and a fuzzy individual ordinal

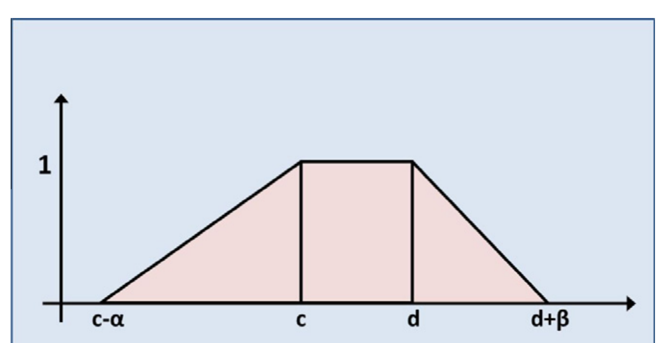

Fig. 3. Trapezoidal fuzzy number.

likelihood matrix is constructed for each mission phase as follows:

$$\widetilde{D}^2(m(b)_j) = \begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_n \end{array} \begin{array}{c} \begin{array}{cccc} x_{1j}(c) & x_{2j}(c) & \cdots & x_{v_j j}(c) \end{array} \\ \begin{bmatrix} \tilde{a}^2_{11}(m(b)_j) & \tilde{a}^2_{12}(m(b)_j) & \cdots & \tilde{a}^2_{1v_j}(m(b)_j) \\ \tilde{a}^2_{21}(m(b)_j) & \tilde{a}^2_{22}(m(b)_j) & \cdots & \tilde{a}^2_{2v_j}(m(b)_j) \\ \vdots & \vdots & \cdots & \vdots \\ \tilde{a}^2_{n1}(m(b)_j) & \tilde{a}^2_{n2}(m(b)_j) & \cdots & \tilde{a}^2_{nv_j}(m(b)_j) \end{bmatrix} \end{array}; \tag{6}$$

where the trapezoidal fuzzy number $\tilde{a}^2_{ih}(m(b)_j)$ is defined with the tolerance interval $[c,d]$, left width α and right width β, and the following membership function ii.:

$$\begin{cases} 1 - \frac{c-t}{\alpha} & \text{if } c - \alpha \leqslant t \leqslant c \\ 1 & \text{if } c \leqslant t \leqslant d \\ 1 - \frac{t-d}{\beta} & \text{if } d \leqslant t \leqslant d + \beta \\ 0 & \text{otherwise} \end{cases}$$

4.1.10. Procedure 1.2.1.3. The construction of the fuzzy individual ordinal detection matrices

According to the PMBOK Guide (2009) for qualitative risk analysis, the detection event is a measure of the ability to predict a specific risk event in the future. Each space exploration team member constructs a fuzzy individual ordinal detection matrix for the mission phase j using the information provided in Steps 1.1.2 and 1.1.4. Considering n mission scenarios, a 1 to n fuzzy number scale is used to represent the detection rating for the failure of an event and a mission scenario in the matrix $\left(1 \leqslant \tilde{a}^3_{ih}(m(b)_j) \leqslant n\right)$. This process is repeated m times and a fuzzy individual ordinal detection matrix is constructed for each mission phase as follows:

$$\widetilde{D}^3(m(b)_j) = \begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_n \end{array} \begin{array}{c} \begin{array}{cccc} x_{1j}(c) & x_{2j}(c) & \cdots & x_{v_j j}(c) \end{array} \\ \begin{bmatrix} \tilde{a}^3_{11}(m(b)_j) & \tilde{a}^3_{12}(m(b)_j) & \cdots & \tilde{a}^3_{1mv_j}(m(b)_j) \\ \tilde{a}^3_{21}(m(b)_j) & \tilde{a}^3_{22}(m(b)_j) & \cdots & \tilde{a}^3_{2v_j}(m(b)_j) \\ \vdots & \vdots & \cdots & \vdots \\ \tilde{a}^3_{n1}(m(b)_j) & \tilde{a}^3_{n2}(m(b)_j) & \cdots & \tilde{a}^3_{nv_j}(m(b)_j) \end{bmatrix} \end{array}; \tag{7}$$

where the trapezoidal fuzzy number $\tilde{a}^3_{nv_j}(m(b)_j)$ is defined with the tolerance interval $[c,d]$, left width α and right width β, and the following membership function iii:

$$\begin{cases} 1 - \frac{c-t}{\alpha} & \text{if } c - \alpha \leqslant t \leqslant c \\ 1 & \text{if } c \leqslant t \leqslant d \\ 1 - \frac{t-d}{\beta} & \text{if } d \leqslant t \leqslant d + \beta \\ 0 & \text{otherwise} \end{cases}$$

4.1.11. Step 1.2.2. The determination of the collective FRPN matrices

In this step, we determine the collective FRPN matrix for each mission phase as follows:

$$\widetilde{D}^{RPN}(j) = \begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_n \end{array} \begin{array}{c} \begin{array}{cccc} x_{1j}(c) & x_{2j}(c) & \cdots & x_{v_j j}(c) \end{array} \\ \begin{bmatrix} \tilde{a}^{RPN}_{11}(j) & \tilde{a}^{RPN}_{12}(j) & \cdots & \tilde{a}^{RPN}_{1v_j}(j) \\ \tilde{a}^{RPN}_{21}(j) & \tilde{a}^{RPN}_{22}(j) & \cdots & \tilde{a}^{RPN}_{2v_j}(j) \\ \vdots & \vdots & \cdots & \vdots \\ \tilde{a}^{RPN}_{n1}(j) & \tilde{a}^{RPN}_{n2}(j) & \cdots & \tilde{a}^{RPN}_{nv_j}(j) \end{bmatrix} \end{array}; \tag{8}$$

where the average impact, likelihood and detection values for each mission phase are calculated as follows:

$$\tilde{a}^1_{ij}(j) = \frac{\sum_{b=1}^{s} \tilde{a}^1_{ij}(m(b)_j)}{s} \tag{9}$$

$$\tilde{a}^2_{ij}(j) = \frac{\sum_{b=1}^{s} \tilde{a}^2_{ij}(m(b)_j)}{s} \tag{10}$$

$$\tilde{a}^3_{ij}(j) = \frac{\sum_{b=1}^{s} \tilde{a}^3_{ij}(m(b)_j)}{s} \tag{11}$$

We then find a collective FRPN value for each mission phase as follows:

$$\tilde{a}^{RPN}_{ij}(j) = \left[\tilde{a}^1_{ij}(j)\right] \cdot \left[\tilde{a}^2_{ij}(j)\right] \cdot \left[\tilde{a}^3_{ij}(j)\right] \tag{12}$$

4.1.12. Process 1.3. The elimination of the mission scenario(s) using the conjunction method

In this process, the space exploration team members collectively define the fuzzy standard levels of risk priority numbers as the maximum acceptable values for accepting or rejecting the mission scenarios. The possible range for $E\left[\tilde{a}^{RPN}_{ih}(j)\right]$, or the expected value of the collective FRPN, is between 1 and n^3. The space exploration team defines a maximum acceptable level of risk in this interval based on their expertise and personal judgment as the fuzzy standard risk priority number with respect to each mission scenario and event. A mission scenario with an event value more than the maximum acceptable level of risk will be rejected. Therefore, A_i is an acceptable mission scenario when:

$$E\left[\tilde{a}^{RPN}_{ih}(j)\right] \leqslant E\left[\tilde{\beta}^{RPN}_{h}(j)\right] h = 1, 2, \ldots, v_j; \quad j = 1, 2, \ldots, m \tag{13}$$

Let us assume that the number of the rejected mission scenarios is z and the remaining (accepted) mission scenarios are represented by the following vector:

$$\underline{A'[r(j)]} = [A_{(1)}[r(j)], A_{(2)}[r(j)], \ldots, A_{(i)}[r(j)], \ldots, A_{(n-z)}[r(j)]] \tag{14}$$

4.1.13. Process 1.4. The development of the best order of the mission scenarios

In this process, we determine the best order of the accepted mission scenarios in each vector $\underline{A'[r(j)]}$. This process is divided into the following three steps:

4.1.14. Step 1.4.1. The determination of the permutations of the mission scenarios in each mission phase

In this step, we test $(n-z)!$ permutations of the mission scenarios for each mission phase. Let us assume that permutation q for mission scenarios in mission phase j is as follows:

$$p^{q_j} = (A_{(1)}(q_j), A_{(2)}(q_j), \ldots, A_{(l)}(q_j), \ldots, A_{(n-z)}(q_j)) \tag{15}$$

4.1.15. Step 1.4.2. The determination of the permutation matrices for each mission phase

For each permutation p^{q_j} of the mission scenarios in mission phase j,we have:

$$P^{q_j} = \begin{array}{c} \\ A_{(1)}(q_j) \\ A_{(2)}(q_j) \\ \vdots \\ A_{(n-z)}(q_j) \end{array} \begin{array}{c} \begin{array}{cccc} A_{(1)}(q_j) & A_{(2)}(q_j) & \cdots & A_{(n-z)}(q_j) \end{array} \\ \begin{bmatrix} 0 & p_{12}^{q_j}(C) & \cdots & p_{1n}^{q_j}(C) \\ p_{12}^{q_j}(D) & 0 & \cdots & p_{2n}^{q_j}(C) \\ \vdots & \vdots & \cdots & \vdots \\ p_{1n}^{q_j}(D) & p_{2n}^{q_j}(D) & \cdots & 0 \end{bmatrix} \end{array} \tag{16}$$

where:

$$p_{kl}^{q_j}(C) = \sum_{h \in C_{kl}(j)} w_h^j(c); \quad h = 1, 2, \ldots, v_j \tag{17}$$

$$p_{kl}^{q_j}(D) = \sum_{h \in D_{kl}(j)} w_h^j(c); \quad h = 1, 2, \ldots, v_j \tag{18}$$

Initially, we define a concordance set of events for each pair of mission scenarios. Let us assume an arbitrary pair of mission scenarios k and l. Then the concordance set $C_{kl}^{(j)}$ associated with mission scenarios (k, l) is defined as follows:$E[\tilde{a}_{kh}^{RPN}(j)] \geqslant E[\tilde{a}_{lh}^{RPN}(j)]$, where the symbol $\geqslant$ represents a weak dominance relationship: mission scenario k is preferred to mission scenario l. The concordance set $C_{kl}^{(j)}$ can be considered as the subset of all events for which a certain mission scenario k is not worse than a competing mission scenario l. Clearly, the total number of concordance sets associated with all pairs of mission scenarios is equal to $(n-z)(n-z-1)$. The complementary set of the concordance set is called the discordance set. The discordance set of mission scenario k and l is defined as: $E[\tilde{a}_{kh}^{RPN}(j)] < E[\tilde{a}_{lh}^{RPN}(j)]$,where the symbol $<$ means: not preferred to. In other words, the discordance set of k with respect to l represents the subset of all events for which mission scenario k is worse than mission scenario l.It is evident that the total number of discordance sets is also equal to $(n-z)(n-z-1)$.

4.1.16. Step 1.4.3. The determination of the best order of the mission scenarios

Let us represent the best order of the mission scenarios for mission phase j with R^{q_j}:

$$R^{q_j} = \sum_{i=1}^{n} \sum_{h=1}^{n} p_{ih}^{q_j}(C) - \sum_{i=1}^{n} \sum_{h=1}^{n} p_{ih}^{q_j}(D) \tag{19}$$

Then, the following matrix represents the best order of the mission scenarios:

$$P_1 = \begin{array}{c} \begin{array}{cccccc} x_1(p) & x_2(p) & \cdots & x_j(p) & \cdots & x_m(p) \end{array} \\ \begin{bmatrix} A_{(1)}[r(1)] & A_{(1)}[r(2)] & \cdots & A_{(1)}[r(j)] & \cdots & A_{(1)}[r(m)] \\ A_{(2)}[r(1)] & A_{(2)}[r(2)] & \cdots & A_{(2)}[r(j)] & \cdots & A_{(2)}[r(m)] \\ \vdots & \vdots & \vdots & \cdots & \vdots & \vdots \\ A_{(n-z)}[r(1)] & A_{(n-z)}[r(2)] & \cdots & A_{(n-z)}[r(j)] & \cdots & A_{(n-z)}[r(m)] \end{bmatrix} \end{array} \tag{20}$$

4.2. Stage 2. The development of the best order of the mission scenarios for the ROA dimension

In this stage, we use ROA to prioritize the mission scenarios according to their costs and benefits. This stage is divided into the following three processes:

4.2.1. Process 2.1. The construction of the individual fuzzy real option matrices

In the first process, each space exploration team member constructs his or her real option matrix based on his or her expertise and judgment where $\tilde{s}$ represents the benefits and $\tilde{x}$ represents the costs associated with mission scenarios $A_{(1)}$ to $A_{(n-z)}$:

$$\widetilde{R}^f(b) = \begin{array}{c} \\ A_{(1)} \\ A_{(2)} \\ \vdots \\ A_{(n-z)} \end{array} \begin{array}{c} \begin{array}{cc} \tilde{s} & \tilde{x} \end{array} \\ \begin{bmatrix} \tilde{s}_1[m(b)_f] & \tilde{x}_1[m(b)_f] \\ \tilde{s}_2[m(b)_f] & \tilde{x}_2[m(b)_f] \\ \vdots & \vdots \\ \tilde{s}_n[m(b)_f] & \tilde{x}_n[m(b)_f] \end{bmatrix} \end{array} (b = 1, 2, \ldots, s) \tag{21}$$

Accordingly, each space exploration team member determines a total cost and total benefit for each mission scenario to be used in $\widetilde{R}^f(b)$. The cost figures, $\tilde{x}_i[m(b)_f]$, for the mission scenarios are subjective numbers used by the team members based on their gut feeling and the previous manned Mars mission studies. One team member might believe that the total costs for the human exploration of Mars would be on the low-side while another team member might believe that the total cost would be on the high-side of the \$20–\$450 billion dollar range estimated by Zubrin and Wagner (1996) and NASA (1989). As for the total benefits figure, $\tilde{s}_i[m(b)_f]$, the team members are advised to use a total benefit figure within a pre-specified and agreed-upon range based on the following five benefits identified by Sadeh and Vlachos (1998): (1) national prestige and leadership; (2) exploration and scientific knowledge; (3) economic growth and development; (4) enabling technologies and technological innovation; and (5) international cooperation.

4.2.2. Process 2.2. The calculation of the fuzzy collective real option matrix

In the second process, the individual fuzzy real option matrices constructed with Eq. (21) are averaged to form the following fuzzy collective real option matrix:

$$\widetilde{R}^f = \begin{array}{c} \\ A_{(1)} \\ A_{(2)} \\ \vdots \\ A_{(n-z_1)} \end{array} \begin{array}{c} \begin{array}{cc} \tilde{s} & \tilde{x} \end{array} \\ \begin{bmatrix} \tilde{s}_1 & \tilde{x}_1 \\ \tilde{s}_2 & \tilde{x}_2 \\ \vdots & \vdots \\ \tilde{s}_n & \tilde{x}_n \end{bmatrix} \end{array} \tag{22}$$

where:

$$\tilde{s}_i = \frac{\sum_{b=1}^{s} \tilde{s}_i[m(b)_f]}{s} \tag{23}$$

$$\tilde{x}_i = \frac{\sum_{b=1}^{s} \tilde{x}_i[m(b)_f]}{s} \tag{24}$$

In the $\widetilde{R}^f$ matrix, $\tilde{s}_i$ is the average of $\tilde{s}_n[m(b)_f]$ and $\tilde{x}_i$ is the average of $\tilde{x}_n[m(b)_f]$ for all space exploration team members ($b = 1, 2, \ldots, s$).

4.2.3. Process 2.3. The determination of the real option value vector and the best order of the mission scenarios

The real option value vector and the best order of the mission scenarios are determined according to the following two steps:

4.2.4. Step 2.3.1. The determination of the real option value vector for the mission scenarios

In this step, a real option value for each mission scenarios, $E(ROV_i)$, is determined using the procedure described next. These real option values form a real option vector, $V(f)$, for all mission scenarios. Initially, a fuzzy real option value for each mission scenario, $R\widetilde{O}V_i$, is calculated using the following equation:

$$R\widetilde{O}V_i = \tilde{s}_i \cdot e^{-\delta} \cdot n(d_{11}) - \tilde{x}_i \cdot e^{-r\cdot} \cdot n(d_{21}) \tag{25}$$

where the cumulative normal probability distributions for $d_1$and d_2 is calculated as follows:

$$N(f) = \begin{array}{c} \\ A_{(1)} \\ A_{(2)} \\ \vdots \\ A_{(n-z)} \end{array} \begin{array}{c} \begin{array}{cc} n(d_1) & n(d_2) \end{array} \\ \begin{bmatrix} n(d_{11}) & n(d_{21}) \\ n(d_{12}) & n(d_{22}) \\ \vdots & \vdots \\ n(d_{1n}) & n(d_{2n}) \end{bmatrix} \end{array} \tag{26}$$

Furthermore, d_{1i} and d_{2i} are calculated using the variance Eq. (32) as follows:

$$d_{1i} = \frac{\ln\left(\frac{E(\tilde{s}_i)}{E(\tilde{x}_i)}\right) + \left(r_i - \delta_i + \sigma_i^2/2\right)}{\sigma_i} \tag{27}$$

$$d_{2i} = \frac{\ln\left(\frac{E(\tilde{s}_i)}{E(\tilde{x}_i)}\right) + \left(r_i - \delta_i - \sigma_i^2/2\right)}{\sigma_i} \tag{28}$$

The following trapezoidal fuzzy numbers are used for the collective fuzzy expected benefits and costs of each mission scenario:

$$\begin{aligned} \tilde{s}_i &= \left((s_i)^c, (s_i)^d, (s_i)^\alpha, (s_i)^\beta\right) \\ \tilde{x}_{i,t_q} &= \left((x_i)^c, (x_i)^d, (x_i)^\alpha, (x_i)^\beta\right) \end{aligned} \tag{29}$$

where the above trapezoidal fuzzy numbers are defined with the tolerance interval $[c, d]$, left width α and right width β, and the following membership function:

$$\begin{cases} 1 - \frac{c-t}{\alpha} & \text{if } c - \alpha \leqslant t \leqslant c \\ 1 & \text{if } c \leqslant t \leqslant d \\ 1 - \frac{t-d}{\beta} & \text{if } d \leqslant t \leqslant d + \beta \\ 0 & \text{otherwise} \end{cases}$$

As a result, $R\widetilde{O}V_i$ would be the following trapezoidal fuzzy number:

$$R\widetilde{O}V_i = \left((ROV_i)^c, (ROV_i)^d, (ROV_i)^\alpha, (ROV_i)^\beta\right); \quad i = 1, 2, \ldots, n - z \tag{30}$$

Next, we use the approach proposed by Carlsson et al. (2007) to determine the following expected value of the total benefits, total costs and real option values for each non-dominated mission scenario; $E(\tilde{s}_i)$, $E(\tilde{x}_i)$ and $E(R\widetilde{O}V_i)$, respectively:

$$\begin{aligned} E(\tilde{s}_i) &= \frac{(s_i)^c + (s_i)^d}{2} + \frac{(s_i)^\beta - (s_i)^\alpha}{6} \\ E(\tilde{x}_i) &= \frac{(x_i)^c + (x_i)^\alpha}{2} + \frac{(x_i)^\gamma - (x_i)^\beta}{6} \\ E(R\widetilde{O}V_i) &= \frac{(ROV_i)^c + (ROV_i)^d}{2} + \frac{(ROV_i)^\beta - (ROV_i)^\alpha}{6}; \\ i &= 1, 2 \cdots n - z \end{aligned} \tag{31}$$

The variance of the non-dominated mission scenarios, σ_i^2; are determined as follows:

$$\sigma_i^2 = \frac{((s_i)^d - (s_i)^c)^2}{4} + \frac{((s_i)^d - (s_i)^c)((s_i)^\alpha + (s_i)^\beta)}{6} + \frac{((s_i)^\alpha + (s_i)^\beta)^2}{24} \tag{32}$$

Consequently, the real option values are used to form the following real option vector for all mission scenarios.

$$V(f) = \begin{array}{c} A_{(1)} \\ A_{(2)} \\ \vdots \\ A_{(n-z_1)} \end{array} \begin{bmatrix} E(ROV_{1,}) \\ E(ROV_2) \\ \vdots \\ E(ROV_n) \end{bmatrix} \quad (33)$$

4.2.5. Step 2.3.2. The determination of the best order of the mission scenarios

In this step, the elements of the vector $V(f)$ presented in Eq. (25) are ranked to identify the best order of the mission scenarios with respect to the ROA dimension:

$$P_2 = \begin{array}{c} x(f) \\ \begin{bmatrix} A_{(1)}[r(f)] \\ A_{(2)}[r(f)] \\ \vdots \\ A_{(n-z)}[r(f)] \end{bmatrix} \end{array} \quad (34)$$

4.3. Stage 3. The development of the best order of the mission scenarios with respect to both the RFMEA and ROA dimensions

In this stage, we aggregate the results of the best order of the mission scenarios according to the RFMEA dimension in Stage 1 and the ROA dimension in Stage 2 using the permutation method described in the following four processes:

4.3.1. Process 3.1. The determination of the ordinal rank matrix

Let us represent P, an ordinal rank matrix for all mission phases, using P_1 in Eq. (20) and P_2 in Eq. (34):

$$P = \begin{array}{c} \begin{array}{ccccccc} x_1(p) & x_2(p) & \cdots & x_m(p) & \cdots & & x(f) \end{array} \\ \begin{bmatrix} A_{(1)}[r(1)] & A_{(1)}[r(2)] & \cdots & A_{(1)}[r(j)] & \cdots & A_{(1)}[r(m)] & A_{(1)}[r(f)] \\ A_{(2)}[r(1)] & A_{(2)}[r(2)] & \cdots & A_{(2)}[r(j)] & \cdots & A_{(2)}[r(m)] & A_{(2)}[r(f)] \\ \vdots & \vdots & & \vdots \cdots & \vdots & & \vdots \\ A_{(n-z)}[r(1)] & A_{(n-z)}[r(2)] & \cdots & A_{(n-z)}[r(j)] & \cdots & A_{(n-z)}[r(m)] & A_{(n-z)}[r(f)] \end{bmatrix} \end{array} \quad (35)$$

4.3.2. Process 3.2. The determination of the mission scenario permutations

In this step, we test $(n-z)!$ mission scenario permutations. Let us assume that the mission scenario permutation q'_j is as follows:

$$p_j^{q'} = \left(A_{(1)}\left(q'_j\right), A_{(2)}\left(q'_j\right), \ldots, A_{(n-z)}\left(q'_j\right)\right) \quad (36)$$

4.3.3. Process 3.3. The determination of the mission scenario permutation matrices

For each mission scenario permutation, we have:

$$P^{q_j} = \begin{array}{c} \\ A_{(1)}\left(q'_j\right) \\ A_{(2)}\left(q'_j\right) \\ \vdots \\ A_{(n-z)}\left(q'_j\right) \end{array} \begin{array}{c} \begin{array}{cccc} A_{(1)}\left(q'_j\right) & A_{(2)}\left(q'_j\right) & \cdots & A_{(n-z)}\left(q'_j\right) \end{array} \\ \begin{bmatrix} 0 & p_{12}^{q'_j}(C) & \cdots & p_{1n}^{q'_j}(C) \\ p_{12}^{q'_j}(D) & 0 & \cdots & p_{2n}^{q'_j}(C) \\ \vdots & \vdots & \cdots & \vdots \\ p_{1n}^{q'_j}(D) & p_{2n}^{q'_j}(D) & \cdots & 0 \end{bmatrix} \end{array} \quad (37)$$

where:

$$p_{kl}^{q'_j}(C) = \sum_{j \in C_{kl}} w_j^{(p)}; \quad j = 1, 2, \ldots, m \quad (38)$$

$$p_{kl}^{q'_j}(D) = \sum_{j \in D_{kl}} w_j^{(p)}; \quad j = 1, 2, \ldots, m \quad (39)$$

The concordance set C_{kl} is a subset of all events for which $A_{(k)}[r(j)] \geqslant A_{(l)}[r(j)]$, and the discordance set D_{kl} is a subset of all events for which $A_{(k)}[r(j)] < A_{(l)}[r(j)]$. (Please see Step 1.4. 2. for a detailed explanation of the concordance and discordance concepts).

4.3.4. Process 3.4. The determination of the optimal mission scenarios

We determine the optimal mission scenario based on the maximum value of $R^{q'_j}$computed over all possible permutations:

$$R^{q'_j} = \sum_{i=1}^{n} \sum_{j=1}^{n} p_{ij}^{q'_j}(C) - \sum_{i=1}^{n} \sum_{j=1}^{n} p_{ij}^{q'_j}(D) \quad (40)$$

5. The case study

The choice of the mission scenario and corresponding trajectory strategy has perhaps the greatest single influence on the success of a manned mission to Mars. In the Human Exploration of Mars Design Reference Architecture 5.0 (2009, p. 47), the Mars Architecture Steering group at NASA Headquarters has identified the ideal mission scenario as "one that provides: (1) the shortest overall mission to reduce the associated human health and reliability risks; (2) adequate time on the surface in which to maximize the return of mission objectives and science; and (3) low mission mass, which, in turn, reduces the overall cost and mission complexity."

As discussed in the previous section, our proposed framework requires the successful utilization of two dimensions: ROA and RFMEA. In the ROA dimension, we considered the costs and benefits associated with each mission scenario; and in the RFMEA dimension, we considered the likelihood, impact and detection of all potential failures associated with the mission scenarios as suggested by

Table 2
The mission phases and their average importance weights.

No.	Mission phase	Weight
1	Earth vicinity/departure	0.099
2	Mars transfer	0.086
3	Mars arrival	0.192
4	Planetary surface	0.151
5	Mars vicinity/departure	0.111
6	Earth transfer	0.129
7	Earth arrival	0.232

objective (2) of the Human Exploration of Mars Design Reference Architecture 5.0 (2009).

In Step 1.1.1 of the proposed framework, the MOD established a team comprised of seven planetary scientists and experts, $\underline{T} = [m(1), m(2), m(3), m(4), m(5), m(6), m(7)]$, selected from various directorates within the JSC to head this effort. The inputs of the various space exploration team members are treated equally in this framework. In Step 1.1.2., the space exploration team identified the following three alternative mission scenarios: split

Table 3
The mission phase events and their importance weights.

Mission phase	Events	Importance Weights
Earth vicinity/ departure	EV1: Transfer to Mars Injection (TMI) miss due to problems with vehicles	0.1866
	EV2: Loss of vehicle due to problems with TMI	0.2139
	EV3: Loss of crew due to problem with TMI	0.2463
	EV4: Post-TMI Earth-return abort options	0.1741
	EV5: Resource Availability for full operations support for all exploration vehicles during Near Earth Operation	0.0697
	EV6: Unplanned shuttle mission to fix problem on MTV	0.1095
Mars transfer	MT1: Need to perform non-surface contingency EVA (Challenging EVA suit design implications)	0.0957
	MT2: Adequate in-situ crew skill development (Computer-based proficiency training and failure simulations)	0.1206
	MT3: Support crew activities (physical/mental health maintenance, protection from solar flare/proton events)	0.2057
	MT4: Ability of the crew/vehicle to resolve serious systems problems without the help of the MCC	0.2660
	MT5: Art. Gravity not being used (no spin-up), resulting in deconditioned crew	0.3121
Mars arrival	MA1: Errors in the post-insertion orbit plane or altitude	0.1309
	MA2: Extended Mars Vicinity Phase	0.1052
	MA3: Errors in aerocapture leading to loss of Crew	0.2124
	MA4: NO GO for Surface descent	0.1674
	MA5: Crew forced to perform strenuous activities during CAP	0.0966
	MA6: Injury to crew during CAP	0.1330
	MA7: Descent problem to cause crew to abort back to Mars Orbit	0.1545
Planetary surface	PS1: Needing contingency surface EVA to restore ascent capability	0.1585
	PS2: Stranded crew on Mars	0.2034
	PS3: Bad weather or other anomaly which could delay ascent, and even require extra EVAs to return to hab	0.1842
	PS4: Early surface mission termination and ascent to Mars orbit	0.1670
	PS5: Meet surface mission constraints and schedule	0.1349
	PS6: Meet Go/No-Go criteria for EVA	0.1520
Mars vicinity/ departure	MV1: NO-GO for ascent	0.1629
	MV2: NO-GO for TEI	0.1516
	MV3: Crew stranded in Mars orbit	0.2127
	MV4: Ascent to lower-than-desired orbit, requiring the return vehicle coming to rescue	0.1855
	MV5: Problems with rendezvous and docking	0.1787
	MV6: Problems with transferring items to return vehicle	0.1086
Earth transfer	ET1: Need to perform non-surface contingency EVA	0.3194
	ET2: Crew's ability to meet their physical fitness activities	0.1771
	ET3: Art. Gravity not being used (no spin-up), resulting in deconditioned crew	0.3021
	ET4: Problems with MCCs	0.2014
Earth arrival	EA1: Loss of Payload	0.1432
	EA2: Loss of crew during direct entry	0.2250
	EA3: Loss of crew during Earth orbit insertion and Shuttle recovery	0.2182
	EA4: Address planetary protection issues	0.1386
	EA5: Problem ditching the NTR stage	0.1227
	EA6: Deconditioned crew having trouble during contingency recovery operations	0.1523

mission,combo lander and dual described earlier in Table 1. In Step 1.1.3, the team identified the following seven mission phases for the human exploration of Mars: Earth vicinity/departure, Mars transfer, Mars arrival,planetary surface, Mars vicinity/departure, Earth transfer and Earth arrival. The mission phases used in this study were identified from the previous architecture studies and anticipated capabilities (Imhof, 2007; Miele et al., 2001). We should note that mission phases may differ for various mission scenarios. For example, there are two vehicles transferring and arriving to Mars in the split mission scenario whereas there is only one vehicle transferring and arriving to Mars in the combo lander scenario. Nevertheless, the team agreed to use seven phases for all mission scenarios uniformly to eliminate additional complexities in the model as a result of using different mission phases for different mission scenarios.

Next, the exploration team used pairwise comparisons and the eigenvalue theory to determine the relative importance of the mission phases. Table 2 presents the seven mission phases and their importance weights. These weights show the relative importance of each mission phase with respect to the overall success of the mission.

In Step 1.1.4, the space exploration team identified 6 events for the Earth vicinity/departure phase, 5 events for the Mars transfer phase, 7 events for the Mars arrival

Table 4
The collective fuzzy impact values.

Mission phase	Events	Mission scenarios		
		Split Mission	Combo Lander	Dual
Earth vicinity/departure	EV1	(0.75, 1.25, 0.25, 0.25)	(1.75, 2.25, 25, 0.25)	(2.75, 3.25, 0.25, 0.25)
	EV2	(2.75, 3.25, 0.25, 0.25)	(1.75, 2.25, 0.25, 0.25)	(0.75, 1.25, 0.25, 0.25)
	EV3	(0.75, 1.25, 0.25, 0.25)	(1.75, 2.25, 0.25, 0.25)	(2.75, 3.25, 0.25, 0.25)
	EV4	(2.25, 2.75, 0.25, 0.25)	(0.75, 1.25, 0.25, 0.25)	(2.25, 2.75, 0.25, 0.25)
	EV5	(0.75, 1.25, 0.25, 0.25)	(2.75, 3.25, 0.25, 0.25)	(1.75, 2.25, 0.25, 0.25)
	EV6	(0.75, 1.25, 0.25, 0.25)	(2.75, 3.25, 0.25, 0.25)	(1.75, 2.25, 0.25, 0.25)
	EV7	(0.75, 1.25, 0.25, 0.25)	(1.75, 2.25, 0.25, 0.25)	(2.75, 3.25, 0.25, 0.25)
Mars transfer	MT1	(1.75, 2.25, 0.25, 0.25)	(2.75, 3.25, 0.25, 0.25)	(0.75, 1.25, 0.25, 0.25)
	MT2	(2.25, 2.75, 0.25, 0.25)	(1.75, 2.25, 0.25, 0.25)	(2.25, 2.75, 0.25, 0.25)
	MT3	(2.75, 3.25, 0.25, 0.25)	(1.25, 1.75, 0.25, 0.25)	(1.25, 1.75, 0.25, 0.25)
	MT4	(1.75, 2.25, 0.25, 0.25)	(2.75, 3.25, 0.25, 0.25)	(0.75, 1.25, 0.25, 0.25)
	MT5	(1.25, 1.75, 0.25, 0.25)	(1.25, 1.75, 0.25, 0.25)	(2.75, 3.25, 0.25, 0.25)
Mars arrival	MA1	(2.75, 3.25, 0.25, 0.25)	(1.75, 2.25, 0.25, 0.25)	(0.75, 1.25, 0.25, 0.25)
	MA2	(2.25, 2.75, 0.25, 0.25)	(2.25, 2.75, 0.25, 0.25)	(0.75, 1.25, 0.25, 0.25)
	MA3	(2.75, 3.25, 0.25, 0.25)	(0.75, 1.25, 0.25, 0.25)	(1.75, 2.25, 0.25, 0.25)
	MA4	(2.25, 2.75, 0.25, 0.25)	(0.75, 1.25, 0.25, 0.25)	(2.25, 2.75, 0.25, 0.25)
	MA5	(2.25, 2.75, 0.25, 0.25)	(0.75, 1.25, 0.25, 0.25)	(2.25, 2.75, 0.25, 0.25)
	MA6	(1.25, 1.75, 0.25, 0.25)	(1.25, 1.75, 0.25, 0.25)	(2.75, 3.25, 0.25, 0.25)
	MA7	(0.75, 1.25, 0.25, 0.25)	(2.25, 2.75, 0.25, 0.25)	(2.25, 2.75, 0.25, 0.25)
Planetary surface	PS1	(0.75, 1.25, 0.25, 0.25)	(1.75, 2.25, 0.25, 0.25)	(2.75, 3.25, 0.25, 0.25)
	PS2	(0.75, 1.25, 0.25, 0.25)	(1.75, 2.25, 0.25, 0.25)	(2.75, 3.25, 0.25, 0.25)
	PS3	(2.25, 2.75, 0.25, 0.25)	(0.75, 1.25, 0.25, 0.25)	(2.25, 2.75, 0.25, 0.25)
	PS4	(2.75, 3.25, 0.25, 0.25)	(1.75, 2.25, 0.25, 0.25)	(0.75, 1.25, 0.25, 0.25)
	PS5	(2.75, 3.25, 0.25, 0.25)	(1.25, 1.75, 0.25, 0.25)	(1.25, 1.75, 0.25, 0.25)
	PS6	(2.75, 3.25, 0.25, 0.25)	(1.75, 2.25, 0.25, 0.25)	(0.75, 1.25, 0.25, 0.25)
Mars vicinity/departure	MV1	(0.75, 1.25, 0.25, 0.25)	(1.75, 2.25, 0.25, 0.25)	(2.75, 3.25, 0.25, 0.25)
	MV2	(0.75, 1.25, 0.25, 0.25)	(2.75, 3.25, 0.25, 0.25)	(1.75, 2.25, 0.25, 0.25)
	MV3	(1.75, 2.25, 0.25, 0.25)	(2.75, 3.25, 0.25, 0.25)	(0.75, 1.25, 0.25, 0.25)
	MV4	(1.75, 2.25, 0.25, 0.25)	(0.75, 1.25, 0.25, 0.25)	(2.75, 3.25, 0.25, 0.25)
	MV5	(2.25, 2.75, 0.25, 0.25)	(2.25, 2.75, 0.25, 0.25)	(0.75, 1.25, 0.25, 0.25)
	MV6	(2.75, 3.25, 0.25, 0.25)	(0.75, 1.25, 0.25, 0.25)	(1.75, 2.25, 0.25, 0.25)
Earth transfer	ET1	(1.75, 2.25, 0.25, 0.25)	(0.75, 1.25, 0.25, 0.25)	(2.75, 3.25, 0.25, 0.25)
	ET2	(0.75, 1.25, 0.25, 0.25)	(2.25, 2.75, 0.25, 0.25)	(2.25, 2.75, 0.25, 0.25)
	ET3	(1.75, 2.25, 0.25, 0.25)	(2.75, 3.25, 0.25, 0.25)	(0.75, 1.25, 0.25, 0.25)
	ET4	(1.75, 2.25, 0.25, 0.25)	(2.75, 3.25, 0.25, 0.25)	(0.75, 1.25, 0.25, 0.25)
Earth arrival	EA1	(0.75, 1.25, 0.25, 0.25)	(1.75, 2.25, 0.25, 0.25)	(2.75, 3.25, 0.25, 0.25)
	EA2	(0.75, 1.25, 0.25, 0.25)	(1.75, 2.25, 0.25, 0.25)	(2.75, 3.25, 0.25, 0.25)
	EA3	(1.75, 2.25, 0.25, 0.25)	(0.75, 1.25, 0.25, 0.25)	(2.75, 3.25, 0.25, 0.25)
	EA4	(0.75, 1.25, 0.25, 0.25)	(1.75, 2.25, 0.25, 0.25)	(2.75, 3.25, 0.25, 0.25)
	EA5	(1.75, 2.25, 0.25, 0.25)	(0.75, 1.25, 0.25, 0.25)	(2.75, 3.25, 0.25, 0.25)
	EA6	(0.75, 1.25, 0.25, 0.25)	(1.75, 2.25, 0.25, 0.25)	(2.75, 3.25, 0.25, 0.25)

phase, 6 events for the planetary surface phase, 6 events for the Mars vicinity/departure phase, 4 events for the Earth transfer phase and 6 events for the Earth arrival mission phase. Next, the exploration team identified the importance weight of the events in each mission phase based on pairwise comparisons and the eigenvalue theory described earlier. A short description of each event along with its importance weight is presented in Table 3.

In Process 1.2, the space exploration team members needed to predict the impact, likelihood and detection ratings for the failure of the events in three mission scenarios. However, there were no similar precedents of these supposed failures, and it was nearly impossible to justify a prediction. In this situation, fuzzy methodology was used to represent the uncertainty. The space exploration team members individually used trapezoidal fuzzy sets to develop a series of impact, likelihood and detection ratings, using a 1–n(1–3 in this case) scale, for all events (associated with the seven mission phases) and the three mission scenarios. The impact fuzzy numbers were used to capture the impact rating for the failure of an event and a mission scenario, the likelihood fuzzy numbers were used to capture the likelihood rating for the failure of an event and a mission scenario, and the detection fuzzy numbers were used to capture the detection rating for the failure of an event and a mission scenario.

Table 5
The collective fuzzy likelihood values.

Mission phase	Events	Mission scenarios		
		Split Mission	Combo Lander	Dual
Earth vicinity/departure	EV1	(0.9, 1.1, 0.1, 0.1)	(2.4, 2.6, 0.1, 0.1)	(2.4, 2.6, 0.1, 0.1)
	EV2	(0.9, 1.1, 0.1, 0.1)	(2.9, 3.1, 0.1, 0.1)	(1.9, 2.1, 0.1, 0.1)
	EV3	(0.9, 1.1, 0.1, 0.1)	(1.9, 2.1, 0.1, 0.1)	(2.9, 3.1, 0.1, 0.1)
	EV4	(1.9, 2.1, 0.1, 0.1)	(0.9, 1.1, 0.1, 0.1)	(2.9, 3.1, 0.1, 0.1)
	EV5	(1.9, 2.1, 0.1, 0.1)	(2.9, 3.1, 0.1, 0.1)	(0.9, 1.1, 0.1, 0.1)
	EV6	(1.4, 1.6, 0.1, 0.1)	(2.9, 3.1, 0.1, 0.1)	(1.4, 1.6, 0.1, 0.1)
	EV7	(1.4, 1.6, 0.1, 0.1)	(1.4, 1.6, 0.1, 0.1)	(2.9, 3.1, 0.1, 0.1)
Mars transfer	MT1	(2.4, 2.6, 0.1, 0.1)	(0.9, 1.1, 0.1, 0.1)	(2.4, 2.6, 0.1, 0.1)
	MT2	(0.9, 1.1, 0.1, 0.1)	(1.9, 2.1, 0.1, 0.1)	(2.9, 3.1, 0.1, 0.1)
	MT3	(0.9, 1.1, 0.1, 0.1)	(2.4, 2.6, 0.1, 0.1)	(2.4, 2.6, 0.1, 0.1)
	MT4	(1.9, 2.1, 0.1, 0.1)	(2.9, 3.1, 0.1, 0.1)	(0.9, 1.1, 0.1, 0.1)
	MT5	(2.9, 3.1, 0.1, 0.1)	(1.4, 1.6, 0.1, 0.1)	(1.4, 1.6, 0.1, 0.1)
Mars arrival	MA1	(1.4, 1.6, 0.1, 0.1)	(1.4, 1.6, 0.1, 0.1)	(2.9, 3.1, 0.1, 0.1)
	MA2	(2.9, 3.1, 0.1, 0.1)	(0.9, 1.1, 0.1, 0.1)	(1.9, 2.1, 0.1, 0.1)
	MA3	(0.9, 1.1, 0.1, 0.1)	(2.9, 3.1, 0.1, 0.1)	(1.9, 2.1, 0.1, 0.1)
	MA4	(0.9, 1.1, 0.1, 0.1)	(2.9, 3.1, 0.1, 0.1)	(1.9, 2.1, 0.1, 0.1)
	MA5	(1.4, 1.6, 0.1, 0.1)	(1.9, 2.1, 0.1, 0.1)	(1.4, 1.6, 0.1, 0.1)
	MA6	(1.4, 1.6, 0.1, 0.1)	(1.4, 1.6, 0.1, 0.1)	(2.9, 3.1, 0.1, 0.1)
	MA7	(1.4, 1.6, 0.1, 0.1)	(1.4, 1.6, 0.1, 0.1)	(2.9, 3.1, 0.1, 0.1)
Planetary surface	PS1	(1.9, 2.1, 0.1, 0.1)	(1.9, 2.1, 0.1, 0.1)	(1.9, 2.1, 0.1, 0.1)
	PS2	(1.4, 1.6, 0.1, 0.1)	(2.9, 3.1, 0.1, 0.1)	(1.4, 1.6, 0.1, 0.1)
	PS3	(1.4, 1.6, 0.1, 0.1)	(1.4, 1.6, 0.1, 0.1)	(2.9, 3.1, 0.1, 0.1)
	PS4	(0.9, 1.1, 0.1, 0.1)	(2.4, 2.6, 0.1, 0.1)	(2.4, 2.6, 0.1, 0.1)
	PS5	(1.9, 2.1, 0.1, 0.1)	(0.9, 1.1, 0.1, 0.1)	(2.9, 3.1, 0.1, 0.1)
	PS6	(0.9, 1.1, 0.1, 0.1)	(2.9, 3.1, 0.1, 0.1)	(1.9, 2.1, 0.1, 0.1)
Mars vicinity/departure	MV1	(0.9, 1.1, 0.1, 0.1)	(2.4, 2.6, 0.1, 0.1)	(2.4, 2.6, 0.1, 0.1)
	MV2	(1.4, 1.6, 0.1, 0.1)	(1.4, 1.6, 0.1, 0.1)	(2.9, 3.1, 0.1, 0.1)
	MV3	(1.9, 2.1, 0.1, 0.1)	(0.9, 1.1, 0.1, 0.1)	(2.9, 3.1, 0.1, 0.1)
	MV4	(1.9, 2.1, 0.1, 0.1)	(0.9, 1.1, 0.1, 0.1)	(2.9, 3.1, 0.1, 0.1)
	MV5	(1.9, 2.1, 0.1, 0.1)	(0.9, 1.1, 0.1, 0.1)	(0.9, 1.1, 0.1, 0.1)
	MV6	(0.9, 1.1, 0.1, 0.1)	(1.9, 2.1, 0.1, 0.1)	(2.9, 3.1, 0.1, 0.1)
Earth transfer	ET1	(1.4, 1.6, 0.1, 0.1)	(2.9, 3.1, 0.1, 0.1)	(1.4, 1.6, 0.1, 0.1)
	ET2	(0.9, 1.1, 0.1, 0.1)	(2.4, 2.6, 0.1, 0.1)	(2.4, 2.6, 0.1, 0.1)
	ET3	(1.9, 2.1, 0.1, 0.1)	(1.9, 2.1, 0.1, 0.1)	(1.9, 2.1, 0.1, 0.1)
	ET4	(1.9, 2.1, 0.1, 0.1)	(1.9, 2.1, 0.1, 0.1)	(1.9, 2.1, 0.1, 0.1)
Earth arrival	EA1	(0.9, 1.1, 0.1, 0.1)	(1.9, 2.1, 0.1, 0.1)	(2.9, 3.1, 0.1, 0.1)
	EA2	(1.9, 2.1, 0.1, 0.1)	(2.9, 3.1, 0.1, 0.1)	(0.9, 1.1, 0.1, 0.1)
	EA3	(1.4, 1.6, 0.1, 0.1)	(1.4, 1.6, 0.1, 0.1)	(2.9, 3.1, 0.1, 0.1)
	EA4	(0.9, 1.1, 0.1, 0.1)	(1.9, 2.1, 0.1, 0.1)	(2.9, 3.1, 0.1, 0.1)
	EA5	(1.9, 2.1, 0.1, 0.1)	(0.9, 1.1, 0.1, 0.1)	(2.9, 3.1, 0.1, 0.1)
	EA6	(0.9, 1.1, 0.1, 0.1)	(2.4, 2.6, 0.1, 0.1)	(2.4, 2.6, 0.1, 0.1)

Following this individual exercise, the team utilized Eqs. (8)–(11) and developed the collective impact, likelihood and detection matrices. As discussed earlier, the trapezoidal fuzzy numbers with the notation $A = (a, b, \alpha, \beta)$ and the tolerance interval $[a, b]$ were used in these matrices to represent the impact, likelihood and detection ratings shown in Tables 4–6.

Next, the team used Eq. (12) to combine the collective impact, likelihood and detection matrices into a single RPN matrix presented in Table 7. Note that the RPN values in this table are between 1 and 3^3 or n^3 where n is the number of mission scenarios and 3 is the number of RFMEA factors.

In Process 1.3, the space exploration team used the historical mission operations data and determined that a score of 23.03 should be used as the maximum threshold value for accepting or rejecting the mission scenarios. In other words, scenarios with the RPN values of greater than 23.03 were considered to pose an unacceptable impact, likelihood and detection risks. Therefore, with regards to Table 7, the dual scenario was rejected and the split mission and combo lander scenarios were identified as feasible mission scenarios with regards to the failure concerns.

In Process 1.4, the team used Eqs. (15)–(20) to identify the best order of mission scenarios for each mission phase with respect to the RFMEA dimension. The best order of

Table 6
The collective fuzzy detection values.

Mission phase	Events	Mission scenarios		
		Split Mission	Combo Lander	Dual
Earth vicinity/departure	EV1	(0.75, 1.25, 0.25, 0.25)	(2.75, 3.25, 0.25, 0.25)	(1.75, 2.25, 0.25, 0.25)
	EV2	(0.75, 1.25, 0.25, 0.25)	(1.75, 2.25, 0.25, 0.25)	(2.75, 3.25, 0.25, 0.25)
	EV3	(0.75, 1.25, 0.25, 0.25)	(1.75, 2.25, 0.25, 0.25)	(2.75, 3.25, 0.25, 0.25)
	EV4	(1.75, 2.25, 0.25, 0.25)	(0.75, 1.25, 0.25, 0.25)	(2.75, 3.25, 0.25, 0.25)
	EV5	(2.75, 3.25, 0.25, 0.25)	(1.25, 1.75, 0.25, 0.25)	(1.25, 1.75, 0.25, 0.25)
	EV6	(0.75, 1.25, 0.25, 0.25)	(2.25, 2.75, 0.25, 0.25)	(2.25, 2.75, 0.25, 0.25)
	EV7	(1.25, 1.75, 0.25, 0.25)	(1.25, 1.75, 0.25, 0.25)	(2.75, 3.25, 0.25, 0.25)
Mars transfer	MT1	(0.75, 1.25, 0.25, 0.25)	(2.75, 3.25, 0.25, 0.25)	(1.75, 2.25, 0.25, 0.25)
	MT2	(1.75, 2.25, 0.25, 0.25)	(0.75, 1.25, 0.25, 0.25)	(2.75, 3.25, 0.25, 0.25)
	MT3	(2.25, 2.75, 0.25, 0.25)	(0.75, 1.25, 0.25, 0.25)	(2.25, 2.75, 0.25, 0.25)
	MT4	(2.25, 2.75, 0.25, 0.25)	(2.25, 2.75, 0.25, 0.25)	(0.75, 1.25, 0.25, 0.25)
	MT5	(1.25, 1.75, 0.25, 0.25)	(1.25, 1.75, 0.25, 0.25)	(2.75, 3.25, 0.25, 0.25)
Mars arrival	MA1	(2.25, 2.75, 0.25, 0.25)	(2.25, 2.75, 0.25, 0.25)	(0.75, 1.25, 0.25, 0.25)
	MA2	(1.75, 2.25, 0.25, 0.25)	(0.75, 1.25, 0.25, 0.25)	(2.75, 3.25, 0.25, 0.25)
	MA3	(0.75, 1.25, 0.25, 0.25)	(2.75, 3.25, 0.25, 0.25)	(1.75, 2.25, 0.25, 0.25)
	MA4	(1.25, 1.75, 0.25, 0.25)	(2.75, 3.25, 0.25, 0.25)	(1.25, 1.75, 0.25, 0.25)
	MA5	(1.75, 2.25, 0.25, 0.25)	(2.75, 3.25, 0.25, 0.25)	(0.75, 1.25, 0.25, 0.25)
	MA6	(2.75, 3.25, 0.25, 0.25)	(1.25, 1.75, 0.25, 0.25)	(1.25, 1.75, 0.25, 0.25)
	MA7	(1.25, 1.75, 0.25, 0.25)	(1.25, 1.75, 0.25, 0.25)	(2.75, 3.25, 0.25, 0.25)
Planetary surface	PS1	(0.75, 1.25, 0.25, 0.25)	(2.25, 2.75, 0.25, 0.25)	(2.25, 2.75, 0.25, 0.25)
	PS2	(0.75, 1.25, 0.25, 0.25)	(2.25, 2.75, 0.25, 0.25)	(2.25, 2.75, 0.25, 0.25)
	PS3	(1.25, 1.75, 0.25, 0.25)	(1.25, 1.75, 0.25, 0.25)	(2.75, 3.25, 0.25, 0.25)
	PS4	(1.25, 1.75, 0.25, 0.25)	(1.25, 1.75, 0.25, 0.25)	(2.75, 3.25, 0.25, 0.25)
	PS5	(1.75, 2.25, 0.25, 0.25)	(0.75, 1.25, 0.25, 0.25)	(2.75, 3.25, 0.25, 0.25)
	PS6	(2.25, 2.75, 0.25, 0.25)	(2.25, 2.75, 0.25, 0.25)	(0.75, 1.25, 0.25, 0.25)
Mars vicinity/departure	MV1	(0.75, 1.25, 0.25, 0.25)	(2.25, 2.75, 0.25, 0.25)	(2.25, 2.75, 0.25, 0.25)
	MV2	(1.75, 2.25, 0.25, 0.25)	(2.75, 3.25, 0.25, 0.25)	(1.75, 2.25, 0.25, 0.25)
	MV3	(2.75, 3.25, 0.25, 0.25)	(1.25, 1.75, 0.25, 0.25)	(1.25, 1.75, 0.25, 0.25)
	MV4	(1.25, 1.75, 0.25, 0.25)	(1.25, 1.75, 0.25, 0.25)	(2.75, 3.25, 0.25, 0.25)
	MV5	(2.25, 2.75, 0.25, 0.25)	(2.25, 2.75, 0.25, 0.25)	(0.75, 1.25, 0.25, 0.25)
	MV6	(0.75, 1.25, 0.25, 0.25)	(2.75, 3.25, 0.25, 0.25)	(1.75, 2.25, 0.25, 0.25)
Earth transfer	ET1	(2.75, 3.25, 0.25, 0.25)	(1.75, 2.25, 0.25, 0.25)	(0.75, 1.25, 0.25, 0.25)
	ET2	(1.25, 1.75, 0.25, 0.25)	(1.75, 2.25, 0.25, 0.25)	(1.25, 1.75, 0.25, 0.25)
	ET3	(0.75, 1.25, 0.25, 0.25)	(2.25, 2.75, 0.25, 0.25)	(2.25, 2.75, 0.25, 0.25)
	ET4	(2.25, 2.75, 0.25, 0.25)	(2.25, 2.75, 0.25, 0.25)	(0.75, 1.25, 0.25, 0.25)
Earth arrival	EA1	(0.75, 1.25, 0.25, 0.25)	(1.75, 2.25, 0.25, 0.25)	(2.75, 3.25, 0.25, 0.25)
	EA2	(2.75, 3.25, 0.25, 0.25)	(1.25, 1.75, 0.25, 0.25)	(1.25, 1.75, 0.25, 0.25)
	EA3	(1.75, 2.25, 0.25, 0.25)	(2.75, 3.25, 0.25, 0.25)	(0.75, 1.25, 0.25, 0.25)
	EA4	(1.25, 1.75, 0.25, 0.25)	(1.25, 1.75, 0.25, 0.25)	(2.75, 3.25, 0.25, 0.25)
	EA5	(1.75, 2.25, 0.25, 0.25)	(0.75, 1.25, 0.25, 0.25)	(2.75, 3.25, 0.25, 0.25)
	EA6	(0.75, 1.25, 0.25, 0.25)	(2.75, 3.25, 0.25, 0.25)	(1.75, 2.25, 0.25, 0.25)

Table 7
The RPN matrix.

Mission phase	Events	Mission scenarios		
		Split Mission	Combo Lander	Dual
Earth vicinity/departure	EV1	1	15	15
	EV2	3	12	6
	EV3	1	8	27
	EV4	10	1	22.5
	EV5	6	13.5	3
	EV6	1.5	22.5	7.5
	EV7	2.25	4.5	27
Mars transfer	MT1	5	9	5
	MT2	5	4	22.5
	MT3	7.5	3.75	9.375
	MT4	10	22.5	1
	MT5	6.75	3.375	13.5
Mars arrival	MA1	11.25	7.5	3
	MA2	15	2.5	6
	MA3	3	9	8
	MA4	3.75	9	7.5
	MA5	7.5	6	3.75
	MA6	6.75	3.375	13.5
	MA7	2.25	5.625	22.5
Planetary surface	PS1	2	10	15
	PS2	1.5	15	11.25
	PS3	5.625	2.25	22.5
	PS4	4.5	7.5	7.5
	PS5	12	1.5	13.5
	PS6	7.5	15	2
Mars vicinity/departure	MV1	1	12.5	18.75
	MV2	3	13.5	12
	MV3	12	4.5	4.5
	MV4	6	1.5	27
	MV5	12.5	18.75	1
	MV6	3	6	12
Earth transfer	ET1	9	6	4.5
	ET2	1.5	12.5	9.375
	ET3	4	15	5
	ET4	10	15	2
Earth arrival	EA1	1	8	27
	EA2	6	9	4.5
	EA3	6	4.5	9
	EA4	1.5	6	27
	EA5	8	1	27
	EA6	1	15	15

the mission scenarios presented in Table 8 was found by calculating the concordance and discordance sets for two permutations of the split mission and combo lander scenarios. The details of concordance and discordance concepts could be found in Step 1.2.2 of Section 4.

In Stage 2, the team used Eqs. (21)–(34) to identify the best order of the mission scenarios with respect to the ROA dimension. Accordingly, mission scenario A_1(split mission scenario) was ranked first and mission scenario A_2(combo lander scenario) was ranked second. These ranking are also shown in Table 8. In Stage 3, the team used matrix (35) and the results obtained from Stage 1 and Stage 2 to determine the best order of the mission scenarios with respect to both dimensions.

Finally, the team used the rankings provided in Table 8 and considered 2! permutations of the mission scenarios using Eqs. (36)–(40) and determined the split mission scenario as the optimal mission scenario. Based on the analysis conducted in this study, the space exploration team concluded that the best mission scenario to Mars is the split mission where a portion of assets required for Mars expedition would be sent to Mars prior to the arrival of the crew. This mission architecture allows a lower-energy/longer-duration trajectory to be utilized for these pre-deployed infrastructures. The ability to pre-deploy some of the mission assets also allows for the preparation of the ascent propellant using the Martian environment as the source for raw materials. The partitioning of the mission elements into pre-deployed cargo and crew vehicles allows the crew to fly on a higher-energy/shorter-duration trajectory, thus minimizing their exposure to the hazards associated with inter-planetary space travel.

In order to test the robustness of our optimal solution, we conducted a sensitivity analysis on the importance weight of the seven mission phases. We considered all 127 possible combinations for changing the importance weight of the mission phases from +1% to +1000%. As shown in Table 9, the optimal solution remained A_1 (split mission scenario) for all changes except for three combinations of 34, 47 and 61. In combination 34, we only changed the importance weights of mission phases 1, 2, 3 and 4. The optimal solution remained A_1 for changes between +1% to +813%. However, the optimal solution changed to A_2 (combo lander scenario) for changes between +814% to +1000%. In combination 47, we only changed the importance weights of mission phases 1, 2, 3 and 6. The optimal solution remained A_1 for changes between +1% to +778%. However, the optimal solution changed to A_2 for changes between +779% to +1000%. In combination 61, we only changed the importance weights of mission phases 1, 2, 3 and 5. The optimal solution remained A_1 for changes between +1% to +743%. However, the optimal solution changed to A_2 for changes between +744% to +1000%.

Table 8
The best order of the mission scenarios.

Rank	The RFMEA dimension							The ROA dimension
	Earth vicinity/ departure	Mars transfer	Mars arrival	Planetary surface	Mars vicinity/ departure	Earth transfer	Earth arrival	
1st	A_1	A_1	A_2	A_1	A_1	A_1	A_1	A_1
2nd	A_2	A_2	A_1	A_2	A_2	A_2	A_2	A_2

Table 9
The sensitivity analysis results.

Mission phase	Combination 34		Combination 47		Combination 61		All other 124 Combinations
1	+1% to +813%	+814% to +1000%	+1% to +778%	+779% to +1000%	+1% to +743%	+744% to +1000%	+1% to +1000%
2	+1% to +813%	+814% to +1000%	+1% to +778%	+779% to +1000%	+1% to +743%	+744% to +1000%	+1% to +1000%
3	+1% to +813%	+814% to +1000%	+1% to +778%	+779% to +1000%	+1% to +743%	+744% to +1000%	+1% to +1000%
4	+1% to +813%	+814% to +1000%	No Change	No Change	No Change	No Change	+1% to +1000%
5	No Change	No Change	No Change	No Change	+1% to +743%	+744% to +1000%	+1% to +1000%
6	No Change	No Change	+1% to +778%	+779% to +1000%	No Change	No Change	+1% to +1000%
7	No Change	No Change	No Change	No Change	No Change	No Change	+1% to +1000%
Optimal Solution	No Change	A2	No Change	A2	No Change	A2	No Change

[i]The expected value of $\tilde{a}^1_{ih}(m(b)_j)$ is then determined by $E\left[\tilde{a}^1_{ih}(m(b)_j)\right] = \frac{\left(a^1_{ih}(m(b)_j)\right)^c + \left(a^1_{ih}(m(b)_j)\right)^d}{2} + \frac{\left(a^1_{ih}(m(b)_j)\right)^\beta - \left(a^1_{ih}(m(b)_j)\right)^\alpha}{6}$.

[ii]The expected value of $\tilde{a}^2_{ih}(m(b)_j)$ is then determined by $E\left[\tilde{a}^2_{ih}(m(b)_j)\right] = \frac{\left(a^2_{ih}(m(b)_j)\right)^c + \left(a^2_{ih}(m(b)_j)\right)^d}{2} + \frac{\left(a^2_{ih}(m(b)_j)\right)^\beta - \left(a^2_{ih}(m(b)_j)\right)^\alpha}{6}$

[iii] The expected value of $\tilde{a}^3_{ih}(m(b)_j)$ is then determined by $E\left[\tilde{a}^3_{ih}(m(b)_j)\right] = \frac{\left(a^3_{ih}(m(b)_j)\right)^c + \left(a^3_{ih}(m(b)_j)\right)^d}{2} + \frac{\left(a^3_{ih}(m(b)_j)\right)^\beta - \left(a^3_{ih}(m(b)_j)\right)^\alpha}{6}$

6. Conclusion and future research directions

Mars is the most accessible planet beyond Moon where sustained human presence is believed to be possible. Selecting an optimal mission scenario for the human exploration of Mars is a complex MADM problem that embraces qualitative and quantitative events. This study was conducted in response to the need for a meaningful and robust aggregation of subjective and objective judgments concerning a large number of competing and conflicting events. Indeed, the templates and models applied in this study could be applied to many other MADM problems.

The proposed method promotes consistent and systematic evaluation of the potential mission scenarios. Evaluations with specific weights and performance scores are used uniformly in the study and applied to all mission scenarios uniformly. Our method provides a consistent combination of all the events among all the selected mission scenarios. Our approach also addresses questions about the sensitivity of the selected mission scenario to changes in the relative importance of the mission phases.

Our model is intended to assist planetary scientists in their mission planning decisions and help them to think systematically about complex exploration mission problems. We decompose the mission scenario selection process into manageable steps and integrate the results to arrive at a solution consistent with mission goals and objectives. This decomposition encourages a careful consideration of the elements of uncertainty. The proposed structured framework does not imply a deterministic approach in mission planning and design. While our approach enables mission planners to assimilate the information from different sources and use fuzzy numbers to partially overcome the arbitrary judgments, it should be used in conjunction with experience and expertise since subjective judgments could bias the final results. Qualitative assessment is an integral component of space mission planning decisions; therefore, the effectiveness of the model relies heavily on the cognitive capabilities of the mission planners.

The framework proposed in this study could potentially be extended to evaluate mission scenarios for Earth orbital operations, architectures without landing on a planetary surface, and potentially even surface operations architectures.

Acknowledgement

This research was supported by NASA grant number NAG 9-39. The lead author is grateful to the Mission Operations Directorate management and staff at the Johnson Space Center for their contributions and assistance with this research project. The authors would like to thank the associate editor, Dr. Alberto Tobias, and the anonymous reviewers for their insightful comments and suggestions.

References

Arney, D., Hickman, J., Tanner, P., Wagner, J., Wilson, M., Wilhite, A. The gryphon: A flexible lunar lander design to support a lunar outpost. Acta Astronaut. 66 (7-8), 1237–1252, 2010.

Bailey, D., Goonetilleke, A., Campbell, D. A new fuzzy multicriteria evaluation method for group site selection in GIS. J. Multicriteria Decision Anal. 12, 337–347, 2003.

Belton, V., Stewart, TJ. Multiple Criteria Decision Analysis: An Integrated Approach. Kluwer, Norwell, 2002.

Bradfield, R., Wright, G., Burt, G., Cairns, G., van Der Heijden, K. The origins and evolution of scenario techniques in long range business planning. Futures 37 (8), 795–812, 2005.

Braun, R.D., Blersch, D.J. Propulsive options for a manned Mars transportation system. J. Spacecraft Rockets 28 (1), 85–92, 1991.

Carbone, T.A., Tippett, D.D. Project risk management using the project risk FMEA. Eng. Manage. J. 16 (4), 28–35, 2004.

Carlsson, C., Fullér, R. A fuzzy approach to real option valuation. Fuzzy Sets Syst. 139 (2), 297–312, 2003.

Carlsson, C., Fullér, R., Heikkilä, M., Majlender, P. A fuzzy approach to R& D project portfolio selection. Int. J. Approx. Reasoning 44 (2), 93–105, 2007.

Chen, T., Zhang, J., Liu, S., Yu, B. Fuzzy Real Option Analysis for IT Investment in Nuclear Power Station, in: Computational Science – ICCS 2007. Springer, Berlin, pp. 953–959, 2007.

Chen, T.-Y., Wang, J.-C. Interval-valued fuzzy permutation method and experimental analysis on cardinal and ordinal evaluations. J. Comput. Syst. Sci. 75, 371–387, 2009.

Cooper, C., Hofstetter, W., Hoffman, J.A., Crawley, E.F. Assessment of architectural options for surface power generation and energy storage on human Mars missions. Acta Astronaut. 66 (7-8), 1106–1112, 2010.

Costa, J.P., Melo, P., Godinho, P., Dias, L.C. The AGAP system: A GDSS for project analysis and evaluation. Eur. J. Oper. Res. 145, 287–303, 2003.

Dawes, R.M. Social selection based on multidimensional criteria. J. Abnormal Soc. Psychol. 68 (1), 104–109, 1964.

Dixit, A., Pindyck, R.S. Investment Under Uncertainty. Princeton University Press, Princeton, 1994.

Donahue, B.B., Cupples, M.L. Comparative analysis of current NASA human Mars mission architectures. J. Spacecraft Rockets 38 (5), 745–751, 2001.

Donahue, B.B. Mars ascent-stage design utilizing nuclear propulsion. J. Spacecraft Rockets 32 (3), 552–558, 1995.

Ehlmann, B.L., Chowdhury, J., Marzullo, T.C., Collins, R.E., Litzenberger, J., Ibsen, S., Krauser, W.R., DeKock, B., Hannon, M., Kinnevan, J., Shepard, R., Grant, F.D. Humans to Mars: A feasibility and cost–benefit analysis. Acta Astronaut. 56 (9-12), 851–858, 2005.

Frode, K. A Real Option Analysis of investments in hydropower: The case of Norway. Energ. Policy 35 (11), 5901–5908, 2007.

Gilboa, Y., Guo, X. Real Option Analysis of a large-scale space solar power venture. Michigan J. Bus. 4 (2), 121–142, 2011.

Gray, A.A., Arabshahi, P., Lamassoure, E., Okino, C., Andringa, J. A real options framework for space mission design. IEEE Aerospace Conf., Big Sky, Montana, 137–146, 2005.

Himmel, S.C., Dugan, J.F., Luidens, R.W., Weber, R.J. A study of manned nuclear-rocket missions to Mars. Aerospace Eng. 20, 51–58, 18 19, 1961.

Hsieh, T.-Y., Lu, S.-T., Tzeng, G.-H. Fuzzy MCDM approach for planning and design tenders selection in public office buildings. Int. J. Project Manage. 22, 573–584, 2004.

Hu, A.H., Hsu, C.-W., Kuo, T.-C., Wu, W.-C. Risk evaluation of green components to hazardous substance using FMEA and FAHP. Expert Syst. Appl. 36 (3), 7142–7147, 2009.

Human Exploration of Mars Design Reference Architecture 5.0. Tech. Rep. NASA-SP-2009-566, in: Bret G. Drake (Ed.), Mars Architecture Steering Group, NASA Headquarters, (<http://www.nasa.gov/pdf/373665main_NASA-SP-2009-566.pdf>), 2009.

Hunt, C.D., vanPelt, M.O. Comparing NASA and ESA cost estimating methods for human missions to Mars, in: 26th International Society of Parametric Analysts Conference, Frascati, Italy, May 10–12, 2004.

Huntley, W.L., Bock, J.G., Weingartner, M. Planning the unplannable: Scenarios on the future of space. Space Policy 26 (1), 25–38, 2010.

Hwang, C.L., Lin, M.J. Group Decision Making under Multiple Criteria. Lec. Notes Econom. Math. Syst., vol. 281. Springer, Berlin, 1987.

Hwang, C.L., Yoon, K. Multiple Attribute Decision Making: Methods and Applications. Springer-Verlag, Berlin/Heidelberg/New York, 1981.

Imhof, B. Configuration options, habitability and architectural aspects of the transfer habitat module (THM) and the surface habitat on Mars (SHM)/ESA's AURORA human mission to Mars (HMM) study. Acta Astronaut. 60 (4-7), 571–587, 2007.

Iz, P., Gardiner, R.L. Analysis of multiple criteria decision support systems for cooperative groups. Group Decision Negot. 2, 61–79, 1993.

Jessup, L.M., Valacich, J.S. Group Support Systems: New Perspectives. Macmillan, New York, 1993.

Kim, S.H., Ahn, B.S. Interactive group decision making procedure under incomplete information. Eur. J. Operat. Res. 116 (3), 498–507, 1999.

Kleindorfer, P.R., Kunreuther, H.C., Schoemaker, P.J.H. Decision Sciences: An Integrative Perspective. Cambridge University Press, New York, 1993.

Klir, G.J., Yuan, B. Fuzzy Sets and Fuzzy Logic: Theory and Applications. Prentice-Hall, New York, 1995.

Koenig, P.C. Real options in ship and force structure analysis: A research agenda. Naval Eng. J. 121 (4), 95–105, 2009.

Kotnour, T., Bollo, T.R. Strategic management of a transformation in a multi-program technology program involving convergence and divergence of programs: observations from NASA. Int. J. Technol. Manage. 53 (2-4), 257–272, 2011.

Landau, D.F., Longuski, J.M. Comparative assessment of human–Mars-mission technologies and architectures. Acta Astronaut. 65 (7-8), 893–911, 2009.

Lavagna, M., Ercoli Finzi, A. A multi-attribute decision-making approach toward space system design automation through a fuzzy logic-based analytic hierarchical process, in: Hendtlass, T., Ali, M. (Eds.), Developments Appl. Artificial Intelligence. Springer-Verlag, London, UK, pp. 596–606, 2002.

Lee, V.A., Wilson, S.W. A survey of ballistic Mars-mission profiles. J. Spacecraft Rockets 4 (2), 129–142, 1967.

Liesiö, J., Mild, P., Salo, A. Preference programming for robust portfolio modeling and project selection. Eur. J. Operat. Res. 181, 1488–1505, 2007.

Mankins, J.C. Affordable Mars exploration architectures: applying systems from the commercial development of space. Acta Astronaut. 50 (1), 27–37, 2002.

Mendell, W.W. Meditations on the new space vision: The moon as a stepping stone to Mars. Acta Astronaut. 57 (2-8), 676–683, 2005.

Mendell, W.W., Heydorn, R.P. Lunar precursor missions for human exploration of Mars – III: studies of system reliability and maintenance. Acta Astronaut. 55, 773–780, 2004.

Miele, A., Wang, T., Mancuso, S. Assessment of launch vehicle advances to enable human mars excursions. Acta Astronaut. 49 (11), 563–580, 2001.

Mikaelian, T., Rhodes, D.H., Nightingale, D.J., Hastings, D.E. Model-based estimation of flexibility and optionability in an integrated real options framework, in: IEEE Syst. Conf., Vancouver, Canada, 224–229, 2009.

Moore, C.L. Technology development for human exploration of Mars. Acta Astronaut. 67 (9-10), 1170–1175, 2010.

Mueller, G.E. An integrated space program for the next generation. Astronaut. Aeronaut. 8, 30–51, 1970.

Murphy, G.M., Thomas, M., Mann, G.A., West, M.D., Clarke, J.D.A., Laing, J.H., Willson, D., Waldie, J.M.A. Testing technologies and strategies for exploration in Australian Mars analogues: A review. Planetary Space Sci. 58 (4), 658–670, 2010.

NASA. Report of the Ninety Day Study on Human Exploration of the Moon and Mars, U.S. Space Council, NASA Headquarters: Washington, DC, 1989.

National Aeronautics and Space Administration. NPR 8715.3 - NASA Safety Manual. Retrieved September 1, 2011 from <http://www.snebulos.mit.edu/projects/reference/NASA-Generic/NPR-8715-3.pdf>, 2011.

O'Brien, F.A. Scenario planning – lessons for practice from teaching and learning. Eur. J. Operat. Res. 152 (3), 709–722, 2004.

Poyhonen, M.A., Hamalainen, R.P., Salo, A.A. An experiment on the numerical modelling of verbal ratio statements. J. Multi-Criteria Decision Anal. 6 (1), 1–10, 1997.

Project Management Institute. A Guide to the Project Management Body of Knowledge (PMBOK® Guide) – 3rd Ed. Project Management Institute, 2009.

Reichert, M. The future of human spaceflight. Acta Astronaut. 49 (3-10), 495–522, 2001.

Rotmans, J., Asselt, M.A., Anastasi, C., Greeuw, S., Mellors, J., Peters, S., Rothman, D., Rijkens, N. Visions for a sustainable Europe. Futures 32 (9-10), 809–831, 2000.

Saaty, T.L. Rank from comparisons and from ratings in the analytic hierarchy/network processes. Eur. J. Operat. Res. 168, 557–570, 2006.

Sadeh, E., Vlachos, E. Human mission from planet Earth: Technology assessment and social forecasting of Moon/Mars Synergies, in: 49th International Astronautical Congress, Melbourne, Australia, 1998.

Salotti, J.M. Simplified scenario for manned Mars missions. Acta Astronaut. 69 (5-6), 266–279, 2011.

Schwartz, P. The Art of the Long View. John Wiley, Chichester, 1996.

Simon, H.A. A Behavioral model of rational choice. Quarterly J. Econom. 69 (1), 99–144, 1955.

Stamatis, D.H. Failure Mode and Effect Analysis. ASQ Quality Press, Milwaukee, 1995.

Tavana, M. A subjective assessment of alternative mission architectures for the human exploration of Mars at NASA using multicriteria decision making. Comput. Operat. Res. 31 (7), 1147–1164, 2004.

Tavana, M. Quest 123: A benchmarking system for technology assessment at NASA. Benchmarking: Int. J. 11 (4), 370–384, 2004.

Tavana, M. A priority assessment multi-criteria decision model for human spaceflight mission planning at NASA. J. Operat. Res. Soc. 57 (10), 1197–1215, 2006.

Tavana, M. A priority assesement multi-criteria decision model for human spaceflight mission planning at NASA. J. Operat. Res. Soc. 57 (20), 1197–1215, 2007.

Tavana, M., Smither, J., Anderson, R.V. D-Side: a facility and workforce planning group multi-criteria decision support system for Johnson Space Center. Comput. & Operat. Res., 34:1646–1673, 2007.

Tavana, M., Hatami-Marbini, A. A group AHP-TOPSIS framework for human spaceflight mission planning at NASA. Expert Syst. Appl. 38 (11), 13588–13603, 2011.

Valls, A., Torra, V. Using classification as an aggregation tool in MCDM. Fuzzy Sets Syst. 15 (1), 159–168, 2000.

van Notten, P.W.F., Rotmans, J., van Asselt, M.B.A., Rothman, D.S. An updated scenario typology. Futures 35 (5), 423–443, 2003.

Villani, G. An R& D investment game under uncertainty in Real Option Analysis. Comput. Econom. 32 (1-2), 199–219, 2008.

von Braun, W. The Mars Project. University of Illinois Press, Urbana, IL, 1953.

von Braun, W., Ryan, C. "Can We Get to Mars?" Collier's Magazine 133, April 30, 1954.

Walberg, G. How shall we go to Mars? A review of mission scenarios. J. Spacecraft Rockets 30 (2), 129–139, 1993.

Yang, J.B., Xu, D.L. On the evidential reasoning algorithm for multiattribute decision analysis under uncertainty. IEEE Trans. Systems Man Cybern. – Part A: Syst. Humans 32 (3), 289–304, 2002.

Yeh, C.H., Deng, H. A practical approach to fuzzy utilities comparison in fuzzy multi-criteria analysis. Int. J. Approx. Reasoning 35 (2), 179–194, 2004.

Zadeh, L.A. Fuzzy sets. Info. Control 8, 338–353, 1965.

Zubrin, R., Wagner, R. The Case for Mars. Simon and Schuster, New York, NY, 1996.