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A Subjective Assessment of Alternative Mission Architecture Operations Concepts for the Human Exploration of Mars at NASA Using a Three-Dimensional Multi-Criteria Decision Making Model

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ABSTRACT

The primary driver for developing missions to send humans to other planets is to generate significant scientific return. NASA plans human planetary explorations with an acceptable level of risk consistent with other manned operations. Space exploration risks can not be completely eliminated. Therefore, an acceptable level of cost, technical, safety, schedule, and political risks and benefits must be established for exploratory missions. This study uses a three-dimensional multi-criteria decision making model to identify the risks and benefits associated with three alternative mission architecture operations concepts for the human exploration of Mars identified by the Mission Operations Directorate at Johnson Space Center. The three alternatives considered in this study include split, combo lander, and dual scenarios. The model considers the seven phases of the mission including: 1. Earth Vicinity/Departure, 2. Mars Transfer, 3. Mars Arrival, 4. Planetary Surface, 5. Mars Vicinity/Departure, 6. Earth Transfer, and 7. Earth Arrival. Analytic Hierarchy Process (AHP) and subjective probability estimation are used to captures the experts' beliefs concerning the risks and benefits of the three alternative scenarios through a series of sequential, rational, and analytical processes.

Key Words: *Multicriteria Decision Making, Group Decision Support Systems, Analytic Hierarchy Process, and Subjective Probabilities.*

THE PROCEDURE

This study considers a five-step procedure that guides the Human Exploration Operations Team (HEOT) at Johnson Space Center through a systematic evaluation of the three mission architecture scenarios including: split, combo lander, and dual.

Split Mission Scenario: 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, the Return Habitat/Ascent Vehicle is launched to Mars. Upon arriving Mars's orbit, the Return Habitat will stay in the orbit while the Ascent Vehicle lands on Mars and starts producing fuel. After the mission equipment are configured and tested to be viable, the Transit Habitat/Surface Habitat is sent initially to Earth's orbit. The crew will be transferred to the Transit Habitat/Surface Habitat in Earth's orbit at a later date. Next, the Transit Habitat/Surface Habitat and the crew are sent to Mars to land near the Ascent Vehicle. After the completion of surface exploration, the Ascent Vehicle is used to transfer the crew to Return Habitat orbiting Mars's orbit. Return Habitat will be used to return the crew to Earth. In all scenarios, travel to and from Mars will take approximately six months each way and surface exploration is scheduled for 520-580 days.

Combo Lander Scenario: In this scenario, the mission assets travel to and from Mars with the crew. Initially Transit Habitat/Surface Habitat/Ascent Vehicle are launched to 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 are sent to Mars with the crew. Upon arriving Mars's orbit, the Transit Habitat separates and remains 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 is used to transfer the crew to Transit Habitat which will return the crew to Earth.

Dual Scenario: In this scenario, Transit Habitat/Surface Habitat/Ascent Vehicle/Descent Vehicle is launched to Earth's orbit. The crew will be transferred to the Transit Habitat/Surface Habitat/Ascent Vehicle/Descent Vehicle in Earth's orbit at a later day. Next, the Transit Habitat/Surface Habitat/Ascent Vehicle/Descent Vehicle is sent to Mars with the crew. In Mars's orbit, Transit Habitat will stay in the orbit, Surface Habitat is landed on Mars unmanned, and the crew uses Ascent/Descent Vehicle to land on Mars near the Surface Habitat. After the completion of surface exploration, the Ascent Vehicle is separated and used to transfer the crew to Transit Habitat which will return the crew to Earth. The five steps are described below:

(i) The HEOT identifies Mission Phases. In this step, the HEOT identifies the phases of mission to be included in the evaluation process. Mission phases considered by the team included Earth Vicinity/Departure, Mars Transfer, Mars Arrival, Planetary Surface, Mars Vicinity/Departure, Earth Transfer, and Earth Arrival.

(ii) HEOT utilizes AHP and EC to determine the importance weight of each Phase. AHP was introduced by Saaty (1972) to assist decision makers in the evaluation of complex judgmental problems. AHP allows the HEOT to assign numerical values to qualitative attributes by making trade-off among them. The process is confined to a series of pairwise comparisons. Saaty (1972) argues that a decision maker naturally finds it easier to compare two things than to compare all the items in a list. AHP also evaluates the consistency of the HEOT and allows for the revision of the responses. Because of the intuitive nature of the process and its power in resolving the complexity in a judgmental problem, AHP has been applied to many diverse decisions. A comprehensive list of the major applications of AHP, along with a description of the method and its axioms, can be found in Saaty (1972, 1977a, 1977b, 1980, and 1990), Weiss and Rao (1987) and Zahedi (1986). AHP has proven to be a very popular technique for determining weights in multicriteria problems (Zahedi 1986 and Shim 1989).

There has been some criticism of AHP in the operations research community. Harker and Vargas (1987) show that AHP does have an axiomatic foundation, the cardinal measurement of preferences is fully represented by the eigenvector method, and the principles of hierarchical composition and rank reversal are valid. On the other hand, Dyer (1990a) has questioned the theoretical basis underlying AHP and argues that it can lead to preference reversals based on the alternative set being analyzed. In response, Saaty (1990) explains how rank reversal is a positive feature when new reference points are introduced. In this study we use the geometric aggregation rule to avoid rank reversal which has had varying degrees of importance to different researchers (Dyer 1990a, Saaty 1990, Harker and Vargas 1990, and Dyer 1990b).

Once the mission phases were identified, the HEOT used a pairwise comparison questionnaire based on AHP to determine the importance weight of each phase. These judgments are synthesized by EC. The normalized geometric means of the HEOTs importance weights of mission phases are calculated at the end of this step.

(iii) The HEOT identifies the criteria to be used for each mission phase and utilize EC to determine the importance weight of their criteria. HEOT as a tem identifies the set of criteria to be used for evaluating the alternative mission architectures. Assume team member i believes $c_1, c_2, \ldots, c_I$ are the I criteria that contribute to the success of a mission architecture. The team member's next task is to assess the relative importance of these criteria using a questionnaire provided based on AHP. The questionnaire asks the team member to compare each possible pair of criteria c_j, c_k and to indicate which of the criteria is more important and by how much.

These judgments are represented by an $I \times I$ matrix:

$$A = (a_{jk}) \qquad (j,k=1, 2, \ldots, I)$$

If c_j is judged to be of equal importance as c_k, then $a_{jk}=1$

If c_j is judged to be more important than c_k, then $a_{jk}>1$

If c_j is judged to be less important than c_k, then $a_{jk}<1$

$$a_{jk} = 1/a_{kj} \qquad a_{jk} \neq 0$$

Thus, matrix A is a reciprocal matrix so that the entry a_{jk} is the inverse of the entry a_{kj}. a_{jk} reflects the relative importance of c_j compared with criteria c_k. For example, $a_{12}=1.25$ indicates that c_1 is 1.25 times as important as c_2.

Then, the vector w representing the relative weights of each of the I criteria can be found by computing the normalized eigenvector corresponding to the maximum eigenvalue of matrix A. An eigenvalue of A is defined as λ which satisfies the following matrix equation:

$$A\,w = \lambda\,w$$

where λ is a constant, called the eigenvalue, associated with the given eigenvector w. Saaty has shown that the best estimate of w is the one associated with the maximum eigenvalue (λ_{max}) of the matrix A. Because the sum of the weights should be equal to 1.00, the normalized eigenvector is used. Saaty's algorithm for obtaining this *w* is incorporated in the software Expert Choice utilized in this study.

One of the advantages of AHP is that it assesses the consistency of the team member's pairwise comparisons. Saaty suggests a measure of consistency for the pairwise comparisons. When the judgments are perfectly consistent, the maximum eigenvalue (λ_{max}) should equal the number of criteria that are compared (*I*). Typically, the responses are not perfectly consistent, and λ_{max} is greater than *I*. The larger the λ_{max}, the greater is the degree of inconsistency. Saaty defines a consistency index (*CI*) as $(\lambda_{\max} - I)/(I - 1)$ and provides a random index (*RI*) table for matrices of order *3* to *10*. This *RI* is based on a simulation of a large number of randomly generated weights.

n	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
RI	*0.58*	*0.90*	*1.12*	*1.32*	*1.41*	*1.45*	*1.49*	*1.51*

Saaty recommends the calculation of a consistency ratio (*CR*) that is the ratio of *CI* to *RI* for the same order matrix. A *CR* of *0.10* or less is considered acceptable. When the *CR* is unacceptable, the team member is informed that the pairwise comparisons are logically inconsistent and is encouraged to revise the EC judgments.

(iv) The HEOT members identify probabilities of occurrence for each factor and each mission phase: Subjective probabilities are commonly used in multicriteria decision making because they require no historical data (Schoemaker 1993, Schoemaker and Russo 1993, Vickers 1992, and Weigelt and Macmillan 1988). Some researchers conclude that the difficulty of obtaining relevant historical information on which to base probabilities inhibits their use. However, probabilistic phrases such as "possible," "likely," "certain," etc. provide an opportunity to elicit the required information verbally and then convert these verbal phrases into numeric probabilities (Brun and Teigen 1988, Budescu and Wallsten 1985, and Tavana et al. 1997). Other commonly used approaches include reasoning (Koriat and Lichtenstein 1980), scenario construction (Schoemaker 1993) and this cross-impact analysis (Stover and Gordon 1978). Merkhofer (1987) and Spetzler and Stael von Holstein (1975) review probability elicitation procedures that are used in practice.

This study utilizes verbal probabilistic scales with probabilistic phrases, like "possible," "likely," and "certain" to elicit the required information and then converts them into numeric probabilities as suggested by Tavana et al. (1997). Alternatively, the HEOT can use numeric probabilities rather than the probabilistic phrases. Each team member receives a listing of all three mission architectures under consideration and assigns probabilities of occurrence to its set of criteria for each mission architecture.

(v) EXCEL is utilized to provide a consensus ranking of the mission architecture scenarios. Microsoft Excel is used in this step to calculate an attractiveness score for each mission architecture scenario using the model presented next.

THE MODEL

To formulate an algebraic model , let us assume:

S^m = Mission architecture score of the *m-th* scenario; ($m = 1, 2, \ldots, q$)

W_i = The importance weight of the *i-th* mission phase; ($i = 1, 2, \ldots, I$)

F_{ij} = The Importance Weight of the *j-th* Criterion for the *i-th* mission phase; ($i = 1, 2, \ldots, I$ and $j = 1, 2, \ldots, J$)

P_{ij}^m = The *m-th* Probability of Occurrence of the *j-th* Criterion for the *i-th* mission phase; ($m = 1, 2, \ldots, q$; $i = 1, 2, \ldots, I$; and $j = 1, 2, \ldots, J$)

I = Number of mission phases

J = Number of Criteria for the *i-th* mission phase

Given the above notations, the overall score of the *m-th* mission architecture scenario is:

$$S^m = \sum_{i=1}^{I} W_i \left(\sum_{j=1}^{J} F_{ij} \left(P_{ij}^m \right) \right)$$

Where:

$$0 \leq P_{ij}^m \leq 1$$

$$\sum_{i=1}^{I} W_i = 1$$

$$\sum_{j=1}^{J} F_{ij} = 1$$

RESULTS AND CONCLUSION

Tables 1 and 2 present the final results of this study. Table 1 shows the average normalized weights assigned to mission architecture phases by the HEOT members. The table also shows the evaluation factors within each phase along with their impact, whether they are perceived as risk or benefit. Risky factors are represented by a (-1) while beneficial factors are represented by a (+1). Table 2 shows the average probabilities of occurrence assigned by the HEOT members along with a final score for each mission architecture scenario. Give the goal of maximizing the overall score, split scenario with an overall score of (-0.124) is the optimal choice followed by dual scenario (-0.145) and the combo lander (-0.169). Further analysis could be done to study the detailed risks and benefits associated with each scenario for each phase.

Insert Tables 1 and 2 Here

This study is not intended to replace human judgment in mission architecture evaluation at Johnson Space Center. In fact, human judgment provides the basic input of to this study. The model used in this study helps HEOTs think systematically about complex mission architecture selection problems and improves the quality of the resulting decisions. Objective data on the characteristics of most scenarios is somewhat limited because of inherent uncertainties. However, experienced HEOTs are often able to provide reasonably accurate estimates of values for these characteristics as a substitute for objective data. This study combines these subjective values numerically to provide an overall score for each mission architecture. It is important to realize that human beings are imperfect information processors and their judgments and preferences about uncertainty can be limited. An awareness of human cognitive limitations is critical in developing the necessary judgmental inputs.

REFERENCES

Dyer, J. S. Remarks on the Analytic Hierarchy Process. *Management Science*. 1990a, 36 (3), 249-258.

Dyer, J. S. A clarification of 'Remarks on the analytic hierarchy process.' *Management Science*, 1990b, 36 (3), 274-275.

Harker, P. T. and Vargas, L. G. Reply to 'Remarks on the analytic hierarchy process' by J. S. Dyer. *Management Science*, 1990, 36 (3), 269-273.

Koriat, A., Lichtenstein, S., and Fischoff, B. Reasons for confidence. *Journal of Experimental Psychology*. 1980, 6, 107-118.

Merkhofer, M. W. Quantifying Judgmental Uncertainty: Methodology, Experiences, and Insights. *IEEE Transactions on Systems, Man, and Cybernetics*. 1987, SMC-17, 741-752.

Saaty, T. L. *An Eigenvalue Allocation Model for Prioritization and Planning*. Energy Management and Policy Center, University of Pennsylvania, 1972.

Saaty, T. L. "A Scaling Method for Priorities in Hierarchical Structures", *Journal of Mathematical Psychology*, 15 (1977a), 234-281.

Saaty, T. L. "Modeling Unstructured Decision Problems: A Theory of Analytical Hierarchies", *Proceedings of the First International Conference on Mathematical Modeling*, (Conference) (1977b), 69-77.

Saaty, T. L. *The Analytic Hierarchy Process*. New York, NY: McGraw-Hill, 1980.

Saaty, T. L. *Multicriteria Decision Making: The Analytic Hierarchy Process*. Pittsburgh: RWS Publications, 1990.

Saaty, T. L. An exposition of the AHP in reply to the paper 'Remarks on the analytic hierarchy process.' *Management Science*, 1990, 36(3), 259-268.

Shim, J. P. Bibliographical research on the Analytic Hierarchy Process (AHP). *Socio-Economic Planning Sciences*. 1989, 23, 161-167.

Spetzler, C. S. and Stael von Holstein, C.- A.S. Probability Encoding in Decision Analysis. *Management Science*, 1975, 22, 340-358.

Stover, J. G., & Gordon, T. J. This study-impact analysis. In J. Fowles (Eds.), *Handbook of futures research*. Westport, CN: Greenwood, 1978.

Tavana, M., Kennedy, D., and Mohebbi, B. An Applied Study Using the Analytic Hierarchy Process to Translate Common Verbal Phrases to Numerical Probabilities. *Journal of Behavioral Decision Making.* 1997, 10(2), 133-150.

Weiss, E. N. and Rao, V. R. "AHP Design Issues for Large-Scale Systems," *Decision Sciences*, 18 (1987), 43-61.

Zahedi, F. "The Analytical Hierarchy Process--A Survey of the Method and Its Applications", *Interfaces*, 16 (1986), 96-108.

TABLE-1: MISSION ARCHITECTURE FACTORS ALONG WITH THEIR PERCEIVED WEIGHTS AND IMPACT

FACTOR	IMPACT	WEIGHT
1. Earth Vicinity/Departure Operations (EV): *LUT clear through* Trans-Mars *Injections*		0.111
EV1: Possibility of TMI miss due to problems with vehicles.	-1	0.066
EV2: Possibility of loss of vehicle due to problems with TMI.	-1	0.130
EV3: Possibility of loss of crew due to problem with TMI.	-1	0.430
EV4: Availability of Post-TMI Earth-return abort options.	+1	0.225
EV5: Availability of existing resources for full operations support for all exploration vehicles during Near Earth	+1	0.088
EV6: Possibility of unplanned shuttle mission to fix problem on MTV.	-1	0.061
2. Mars Transfer Operations (MT): Burnout of the TMI maneuver until x hours before Mars Orbital		0.084
MT1: Possibility of need to perform non-surface contingency EVA (Challenging EVA suit design implications –	-1	0.478
MT2: Probability of adequate in-situ crew skill development (Computer-based proficiency training and failure	+1	0.186
MT3: Ability to support crew activities (physical and mental health maintenance, warning of and protection from	+1	0.094
MT4: Ability of the crew/vehicle to resolve serious systems problems without the help of the MCC.	+1	0.186
MT5: Possibility of Art. Gravity not being used (no spin-up), resulting in deconditioned crew.	-1	0.056
3. Mars Arrival Operations (MA): MOI minus x hours through the post landing, Crew Adaptation Phase		0.190
MA1: Possibility of errors in the post-insertion orbit plane or altitude.	-1	0.110
MA2: Possibility of an Extended Mars Vicinity Phase.	-1	0.124
MA3: Possibility of errors in aerocapture leading to loss of Crew.	-1	0.402
MA4: Possibility of NO GO for Surface descent.	-1	0.051
MA5: Possibility of crew having a need to perform strenuous activities during CAP.	-1	0.077
MA6: Possibility of injury to crew during CAP.	-1	0.143
MA7: Possibility of descent problem to cause crew to abort back to Mars Orbit.	-1	0.094
4. Planetary Surface Operations (PS): End of CAP to the initiation of the Surface Ascent Terminal		0.149
PS1: Possibility of needing contingency surface EVA to restore ascent capability.	-1	0.159
PS2: Possibility of crew stranded on Mars.	-1	0.437
PS3: Possibility of bad weather or other anomaly which could delay ascent, and even require extra EVAs to return	-1	0.131
PS4: Possibility of early surface mission termination and ascent to Mars orbit.	-1	0.091
PS5: Ability to meet surface mission constraints and schedule.	+1	0.078
PS6: Ability to meet Go/No-Go criteria for EVA.	+1	0.103
5. Mars Vicinity/Departure Operations (MV): The initiation of the SATC through the Trans-Earth		0.109
MV1: Probability of NO-GO for ascent.	-1	0.277
MV2: Probability of NO-GO for TEI.	-1	0.161
MV3: Possibility of crew stranded in Mars orbit.	-1	0.328
MV4: Possibility of ascent to lower-than-desired orbit, requiring the return vehicle coming to rescue.	-1	0.092
MV5: Possibility of problems with rendez and docking.	-1	0.096
MV6: Possibility of problems with transferring items to return vehicle.	-1	0.045
6. Earth Transfer Operations (ET): Post-TEI to x hours prior to Earth Orbital Insertion		0.127
ET1: Possibility of need to perform non-surface contingency EVA.	-1	0.494
ET2: Crew's ability to meet their physical fitness activities.	1	0.230
ET3: Possibility of Art. Gravity not being used (no spin-up), resulting in deconditioned crew.	-1	0.163
ET4: Possibility of problems with MCCs.	-1	0.113
7. Earth Arrival Operations (EA): Defined as x hours prior to EOI to Crew Egress.		0.229
EA1: Possibility of loss of Payload	-1	0.036
EA2: Possibility of loss of crew during direct entry.	-1	0.308
EA3: Possibility of loss of crew during Earth orbit insertion and Shuttle recovery.	-1	0.308
EA4: Ability to address planetary protection issues.	1	0.122
EA5: Possibility of problem ditching the NTR stage.	-1	0.130
EA6: Possibility of deconditioned crew having trouble during contingency recovery operations.	-1	0.095

TABLE-2: MISSION ARCHITECTURE SCENARIOS ALONG WITH THEIR PROBABILITIES OF OCCURRENCE

FACTOR	SPLIT	COMBO	DUAL
1. Earth Vicinity/Departure Operations (EV)			
EV1	35.71%	45.71%	45.71%
EV2	27.14%	31.43%	24.29%
EV3	17.14%	22.86%	22.86%
EV4	47.14%	38.57%	47.14%
EV5	45.71%	37.14%	38.57%
EV6	24.29%	32.86%	30.00%
2. Mars Transfer Operations (MT)			
MT1	32.42%	41.43%	60.56%
.MT2	78.57%	74.29%	75.71%
MT3	74.29%	74.29%	81.43%
MT4	65.71%	65.71%	65.71%
MT5	71.43%	72.86%	64.29%
3. Mars Arrival Operations (MA)			
MA1	24.29%	25.71%	28.57%
MA2	34.29%	30.00%	31.43%
MA3	37.14%	32.86%	32.86%
MA4	24.29%	25.71%	25.71%
MA5	31.43%	31.43%	32.86%
MA6	25.71%	24.29%	25.71%
MA7	27.14%	21.43%	21.43%
4. Planetary Surface Operations (PS)			
PS1	32.86%	37.14%	41.43%
PS2	12.22%	55.71%	28.57%
PS3	34.29%	37.14%	38.57%
PS4	30.00%	28.57%	35.71%
PS5	52.86%	55.71%	57.14%
PS6	58.57%	54.29%	61.43%
5. Mars Vicinity/Departure Operations (MV)			
MV1	31.43%	30.00%	25.71%
MV2	25.71%	30.00%	31.43%
MV3	25.71%	24.29%	27.14%
MV4	24.29%	24.29%	22.86%
MV5	25.71%	22.86%	37.14%
MV6	30.00%	27.14%	20.00%
6. Earth Transfer Operations (ET)			
ET1	40.00%	44.29%	41.43%
ET2	61.43%	62.86%	60.00%
ET3	55.71%	60.00%	55.71%
ET4	24.29%	27.14%	24.71%
7. Earth Arrival Operations (EA)			
EA1	24.29%	21.43%	18.57%
EA2	22.86%	27.14%	27.14%
EA3	21.43%	31.43%	22.86%
EA4	60.00%	58.57%	68.57%
EA5	28.57%	31.43%	38.57%
EA6	50.00%	42.86%	50.00%
TOTAL SCORE	**-0.124**	**-0.169**	**-0.145**