APPLICATION OF MULTIPLE CRITERIA DECISION METHODS IN SPACE EXPLORATION INITIATIVE DESIGN AND PLANNING

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My 1991 NASA/ASEE Summer Faculty Fellowship activities at the Langley Research Center (LaRC) were directed towards the identification of the opportunities for application of Multiple Criteria Decision Making (MCDM) techniques in the Space Exploration Initiative (SEI) domain. I identified several application possibilities and proposed demonstration application in these three areas: (1) evaluation and ranking of SEI architectures, (2) space mission planning and selection, and (3) space system design. Due to page limitations, this report describes only the results of my research efforts directed towards the first problem. A more detailed report about all three problems would be issued later.

SEI Architectures

SEI represents the focused efforts by NASA in meeting President Bush's challenge to the American's, made on the 20th anniversary of first manned Moon landing, to go "..back to the Moon.. (and this time) to stay... and a manned mission to Mars." Accordingly, several studies have been conducted to define strategies about how this can be accomplished. One of the first detailed report discussing scenarios (called "architectures") for Mars missions is the "90-day Study" report by NASA[1]; and, the most recent one is the report of the "Synthesis Group" set up by Vice-President Quayle[2]. NASA would now be conducting additional technical studies to arrive at a baseline SEI architecture. My research was aimed towards demonstrating that MCDM methods can assist in this. The following five architectures were chosen for evaluation and ranking:

- A : Architecture I (Mars Exploration) of the Synthesis Group Report.
- B : Architecture II (Science Emphasis for the Moon and Mars) of the Synthesis Group Report.
- C : Architecture III (Moon to Stay and Mars Exploration) of the Synthesis Group Report.
- D : Architecture IV (Space Resource Utilization) of the Synthesis Group Report.
- E : Modified Reference Architecture of the 90-Day Study Report.

Evaluation Criteria

Several researchers from the SEI Office at LaRC participated in the development of a two-level, hierarchically structured set of general evaluation criteria. Specific, technical criteria were not deemed to be relevant at this early stage of architectural concepts. Table 1 shows the developed criteria set.

Relative Importance of the Evaluation Criteria
Many approaches for the development of relative importance weights are available[3]. We have used the concept proposed by Saaty for Analytic Hierarchy Process (AHP). Using the scale shown in Table 2, SEI researchers first made pairwise comparisons of the major criteria. Weights for these major criteria were then computed from these comparisons; see column 2 of Table 3. Next, they made pairwise comparisons of the sub-criteria under each major criterion. Weights from these comparisons and the weights of the major criteria computed previously were used to determine the absolute weights of each sub-criterion. Finally, sub-criteria with only marginal effects were combined, to reduce the set of the evaluation criteria. Table 3 shows the resultant reduced set of evaluation criteria and the corresponding weights.

Evaluation of the Architectures
Each of the five architectures were then evaluated by the SEI researchers with respect to each the sub-criterion. The scale in Table 4 was used in these evaluations, and the results are shown in Table 5.

Rank Ordering of the Architectures
Different rank ordering methods, such as Simple Additive Weighing, ELECTRE and TOPSIS, are available. We have used TOPSIS by Hwang and Yoon[3]. TOPSIS uses the Euclidian distance of each alternative from an "Ideal Solution" (constructed from the best achieved value with respect to each criterion by any of the alternatives under consideration) and a "Negative Ideal Solution" (constructed from the worst criteria values of all the alternatives) to compute a closeness measure, C_*. The closeness measure for an alternative equals 1 when it coincides with the "Ideal Solution" and the measure equals 0 when the alternative coincides with the "Negative Ideal Solution." Table 6 shows the computed closeness measure values for all five of the architectures, and their final ranking.

Concluding Remarks
The most meaningful result from this analysis is the wide separation between the top two ranked architectures, indicating a significant preference difference between them. It must also be noted that the final ranking reflects, to some extent, the biases of the evaluators and their understanding of the architectures.

REFERENCES
1. Report of the 90-Day Study on Human Exploration of the Moon and Mars. NASA Internal Report, Johnson Space Center (Aaron Cohen, Study Leader), November, 1989.
2. America at the Threshold : America's Space Exploration Initiative. Final report of the Synthesis Group (Thomas Stafford, Group Leader), May, 1991.
3. Hwang, C.L. and K. Yoon, Multiple Attribute Decision Making : Methods and Applications. Springer-Verlag, New York, 1981.

Table 1. Evaluation Criteria

Criterion	Sub-criterion	Explanation
Maximize the following criteria (i.e., the more the better)		
1. Utility/Benefit		
	1.1 Economical	Potential national economic payoffs
	1.2 Technological	Technological Payoffs/spinoffs
	1.3 Educational	Impact on national education system
	1.4 Scientific	Impact on scientific knowledge
	1.5 Commercial	Potential for commercial payoffs
	1.6 Synergy	Positive (synergistic) effect on other SEI/Civilian space projects
	1.7 Visibility	Public visibility and appeal
	1.8 International Cooperation	Degree of International cooperation that may be achieved
	1.9 Political	Political appeal and attractiveness
2. Feasibility		
	2.1 Technical	Soundness and reasonableness of the technological state-of-the-art assumptions
	2.2 Schedule	Functionality and reasonableness of the schedule
	2.3 Political	Potential for public/congress support
3. Flexibility		
	3.1 Launch Date	Flexibility in launch date
	3.2 Budget	Flexibility in the required budget
	3.3 Schedule	Flexibility in the overall schedule (resiliency in the schedule)
	3.4 Mission	Adaptability to changes in the mission goal, focus, etc.
	3.5 Design	Robustness of the architectural design
4. Manageability		
	4.1 Developmental	Degree of difficulty in the management of the development efforts
	4.2 Operational	Degree of difficulty in the management of the mission operations
Minimize the following criteria (i.e., the less the better)		
5. Risk/Uncertainty		
	5.1 Crew Safety	Potential risk in crew safety and health
	5.2 Technological	Risk that the expected technology would not be developed at all or in a timely manner
	5.3 Economical	Economic risk/uncertainty (potential, and degree thereof, for the budget to increase)
	5.4 Schedule	Robustness of the schedule (level of uncertainty in the schedule)
	5.5 Performance	Potential uncertainty about achieving the expected performance
6. Cost		
	6.1 Life Cycle Cost	Total developmental and operating cost
	6.2 Conflict	Potential for detrimental effect on other SEI/Civilian space projects?

Table 2. Pairwise Preference Measurement Scale

Intensity of Importance of criterion C_1 over criterion C_2	Definition	Explanation
1	Equal importance	C_1 and C_2 are equally important
3	Weak importance	Experience & judgement slightly favor C_1 over C_2
5	Essential or strong importance	Experience & judgement strongly favor C_1 over C_2
7	Demonstrated importance	C_1 is strongly favored & its dominance is demonstrated in practice
9	Absolute importance	The evidence favoring C_1 over C_2 is of the highest possible order of affirmation
2,4,6,8	Intermediate values	When compromise is needed between two adjacent judgements

Table 3 Final Weights of Evaluation Criteria

Criterion	Weight	Sub-criterion	Weight	
			Relative	Absolute
Utility/Benefit	0.0754			
		Economical/ Technological/ Educational	0.2279	0.0172
		Scientific	0.2314	0.0175
		Visibility	0.2511	0.0189
		Political	0.2896	0.0218
Feasibility	0.3179			
		Technical	0.2211	0.0703
		Schedule	0.4600	0.1462
		Political	0.3190	0.1014
Flexibility	0.0774			
		Launch Date/ Schedule	0.2192	0.0170
		Mission	0.6095	0.0471
		Design	0.1713	0.0133
Manageability	0.0331			0.0331
Risk/Uncertainty	0.3610			
		Crew Safety	0.6544	0.2362
		Technological/ Performance	0.1690	0.0610
		Economical/ Schedule	0.1766	0.0638
Cost	0.1349			
		Life Cycle Cost	0.9000	0.1214
		Conflict	0.1000	0.0135

Table 4. Architecture Evaluation Scale

For Cost Attributes			For Benefit Attributes
	0	0	
very high	1.0	1.0	very low
high	3.0	3.0	low
average	5.0	5.0	average
low	7.0	7.0	high
very low	9.0	9.0	very high
	10.0	10.0	

Table 5. Architecture Evaluation Matrix

(Sub) Criterion	Architecture Evaluation				
	A	B	C	D	E
Econ/Tech/Educ Benefit	6	7	8	7	6
Scientific Benefit	6	9	8	5	5
Visibility Benefit	6	8	9	6	6
Political Benefit	6	7	6	7	6
Technical Feasibility	7	5	6	3	9
Schedule Feasibility	4	2	1	2	9
Political Feasibility	5	5	1	5	8
Launch/Schedule Flexibility	5	5	3	5	7
Mission Flexibility	7	5	8	5	7
Design Flexibility	6	6	6	6	7
Manageability	6	5	4	5	8
Crew Safety Risk	6	6	4	6	6
Techn/Performance Uncertainty	4	4	3	4	6
Econ/Schedule Uncertainty	5	3	3	2	7
Life Cycle Cost	5	2	5	7	7
Conflict Cost	3	2	1	2	5

Table 6. Ranking of the Architectures

Architecture	Separation Measures		Relative Closeness C_{i*}	Rank
	(From A^*) S_{i*}	(From A^-) S_{i-}		
A	0.08135	0.11308	0.5816	2
B	0.12002	0.05481	0.3135	4
C	0.14060	0.03552	0.2017	5
D	0.11353	0.07253	0.3898	3
E	0.00724	0.15107	0.9543	1