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Paper Session III-C - Reaction Control System Propellant Trade Study: An Application of the Analytic Hierarchy Process

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Reaction Control System Propellant Trade Study: An Application of the Analytic Hierarchy Process

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Abstract

Decision making is often difficult because tradeoffs must be made among competing objectives. In order to make tradeoffs, decision makers must be able to evaluate and measure each aspect of the decision – some quantitative, some qualitative, some very important, and some not so important. Uncertainties and competing interest groups also add to the complexity of decision making.

The analytic hierarchy process (AHP) is a multicriterion (or multiobjective) decision support methodology. AHP makes it possible for decision makers to deal with both tangible and intangible factors. Data, thoughts, and intuition are organized in a logical, hierarchical structure. Decision makers can express their understanding and experience with pairwise comparisons about the relative importance or preference of all relevant factors. AHP allows for revision for sensitivity analyses. The results of an AHP are easily tested for sensitivities to changes in assumptions and judgments.

Current Space Shuttle hypergolic propellant systems servicing is extremely hazardous and performed at three different facilities at the Kennedy Space Center (KSC). These facilities are the Orbiter Processing Facility (OPF), the Hypergolic Maintenance Facility (HMF), and Launch Complex 39 (LC-39). Propellant systems servicing in the OPF and at LC-39 must be scheduled with processing of other Space Shuttle systems. Serial processing time is incurred in any facility with hazardous operations.

Alternative propellants were considered in a trade study for use on a proposed reaction control system (RCS). Specifically hydrogen peroxide (H_2O_2)/rocket propellant 1 (RP-1) were analyzed versus the currently used nitrogen tetroxide (N_2O_4)/monomethythydrazine (MMH). The purpose of the trade study was to identify impacts or potential savings in facilities, equipment, and processing tasks for the RCS. AHP was used as a significant decision making aid in obtaining the study results.

Introduction

Current Space Shuttle hypergolic propellant systems servicing is extremely hazardous and performed at three different facilities at the Kennedy Space Center (KSC). These facilities are the Orbiter Processing Facility (OPF), the Hypergolic Maintenance Facility (HMF), and Launch Complex 39 (LC-39). The hypergolic propellant used by the Space Shuttle, nitrogen tetroxide (N_2O_4) and monomethylhydrazine (MMH), offers some significant advantages. Hypergolic propellants can be stored for long periods of time and can be used in relatively simple engines that may be started and stopped easily.

However N_2O_4/MMH are also toxic and corrosive, giving rise to human health risks and other problems. Launch processing personnel must be protected by special suits from exposure to carcinogenic or corrosive materials. When propellant technicians work with these fluids, other launch personnel must evacuate the area. Propellant systems servicing in the OPF and at LC-39 must be scheduled with processing of other Space Shuttle systems. Serial processing time is incurred in any facility with hazardous operations.

Less toxic propellants are desired for future space transportation vehicles in order to mitigate some of the launch processing problems discussed above. Alternative propellants were considered in a trade study for use on a proposed reaction control system (RCS). Specifically hydrogen peroxide (H_2O_2)/rocket propellant 1 (RP-1) were analyzed versus the currently used N_2O_4/MMH. The purpose of the trade study was to identify impacts or potential savings in facilities, equipment, and processing tasks for the RCS.

There are a number of methodologies which can be used to aid in the resolution of this multiple attribute decision problem. These include realitively simple techniques such as graphical, tabular, and additive weighting and more detailed, quantitative methodologies such as multiattribute utility modeling, the analytic hierarchy process (AHP), goal programming, and expert systems. The selection of multiattribute decision analysis (MADA) methodology depends on the nature of the decision problem and the preferences of the decision maker(s). Practical experience has shown that the use of differing models will have less effect on the quality of the solution than does the unintended omission of alternatives or important criteria [Canada, p. 237]. The strength of the AHP lies in its ability to: (i) structure a complex, multiattribute problem hierarchically, (ii) estimate preferences for competing alternatives and attributes using simple pairwise comparisons, and (iii) determine the consistency of the decision maker's preferences. This paper describes an AHP model of the RCS propellant trade study, discusses results obtained using a spreadsheet model verified with the *Expert Choice* software package, and draws relevant conclusions.

The Analytic Hierarchy Process Decision Model

The general approach of the AHP is to decompose the problem and to make pairwise comparisons of all elements (i.e., attributes, alternatives, etc.) on a given level with respect to the related elements in the level just above. The degree of preference or intensity of the decision maker in the choice for each pairwise comparison is quantified on a scale of 1 to 9, and these quantities are placed in a matrix of comparisons [Canada, p.260]. Table 1 shows the fundamental verbal and numerical scales used to express judgments, and the relationship between them [Expert Choice, p. v].

A matrix of comparisons for all elements is constructed with preference numbers obtained from Table 1. For inverse comparisons, the reciprocal of the preference number is used. The solution process consists of three stages, with an optional (recommended) concurrent fourth stage as follows [Canada, pp. 260 - 262]:

1. Determine the relative importance of the attributes and subattributes, if any.
2. Determine the relative standing (weight) of each alternative with respect to each subattribute, if applicable, and then successively with respect to each attribute.
3. Determine the overall priority weight (score) of each alternative.
4. Determine the indicator of consistency in making pairwise comparisons.

Table 1. AHP modes of comparison

Numerical Scale	Verbal Scale	Explanation
1	Equal importance of both elements	Two elements contribute equally to the property
3	Moderate importance of one element over the other	Experience and judgment favor one element over the other
5	Strong importance of one element over the other	An element is strongly favored
7	Very strong importance of one element over the other	An element is strongly dominated
9	Extreme importance of one element over the other	An element is favored by at least an order of magnitude of difference
2, 4, 6, 8	Intermediate values between two adjacent judgments	Used for compromise between two judgments

Figure 1 contains the four-level decision hierarchy for the RCS propellant trade study. The top of the hierarchy (Level I) contains the overall goal or focus objective of the trade study; to select the best RCS propellant from among the two alternatives. Level II of the hierarchy contains the main attributes identified by the trade study's decision maker. Level III contains the subattributes identified by the trade study's decision maker. Hierarchy Level

IV contains the two propellant alternatives for the trade study. Figure 1 illustrates the parent-child relationships between attributes, subattributes, and alternatives.

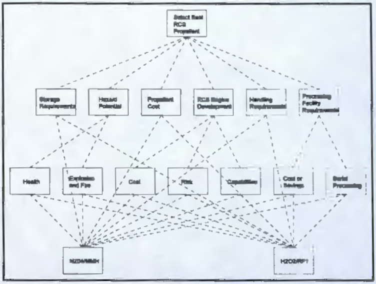

Figure 1. Decision hierarchy for selecting the best RCS propellant

Table 2 describes the attribute and alternative variable used throughout this study. Subattributes are shown with bullets and indented in Table 2. Figure 2 shows the decision maker's preference comparisons for the main attributes.

Table 2. AHP model attribute and alternative symbols and meanings

Symbol	Meaning
STORAGE	Propellant storage requirements
HAZARD	Propellant hazard potential
• HEALTH	Propellant health hazard
• EXPLOSIV	Propellant explosion and fire hazard
PRO_COST	Propellant procurement cost
ENGINE	RCS engine development
• ENG_COST	RCS engine development cost
• RISK	RCS engine development risk
• CAPABIL	RCS engine performance capabilities
HANDLING	Propellant handling/transportation requirements
FACILITY	RCS/vehicle processing facility requirements
• COST/SAV	RCS/vehicle processing facility build/mod cost or reallocation savings
• SRL_PRCS	RCS/vehicle processing facility serial processing requirements/impacts
N204/MMH	N_2O_4/MMH alternative (hypergolic)
H2O2/RP1	H_2O_2/RP1 alternative (non-hypergolic)

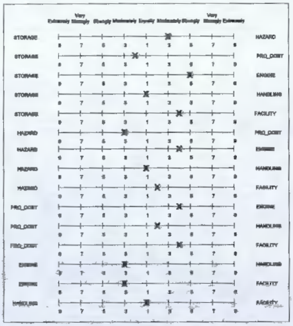

Figure 2. Main attribute preference comparisons with respect to the focus objective

Model Calculations and Solution

Figure 3 is a spreadsheet representation of the decision maker's pairwise preference for main attributes with respect to the focus objective. The estimate a_{ij} reflects the ratio of the decision maker's preference for row attribute i relative to column attribute j. Note that each a_{ij} on the diagonal of the preference matrix has value 1. Also note that because of the ratio scale: $a_{ij} = 1/a_{ji}$. To assist in developing the ratio scale estimates, the verbal-to-numerical scale shown in Table 1 was used. For example, the importance of propellant hazard potential (HAZARD) is moderately (3) more important than propellant storage requirements (STORAGE).

	STORAGE	HAZARD	PRO_COST	ENGINE	HANDLING	FACILITY
STORAGE	1	1/3	2	1/5	1	1/4
HAZARD	3	1	3	1/4	1	1/2
PRO_COST	1/2	1/3	1	1/4	1/2	1/4
ENGINE	5	4	4	1	3	3
HANDLING	1	1	2	1/3	1	1
FACILITY	4	2	4	1/3	1	1
Total	14.500	8.667	16.000	2.367	7.500	6.000

Figure 3. Preference comparisons with respect to the focus objective

Figure 4 contains the results of normalizing the preference comparisons in Figure 3. The attribute columns are normalized to sum to one by dividing each element in Figure 3 by the column total. In the last two columns of Figure 4, the row elements are summed and the averages of those row elements (principal vector) are found by dividing by six. The results (principal vector) are the main attribute priority weights. Note that below these weights is the consistency ratio (CR) determined by the *Expert Choice* software package.

[Saaty] suggested an empirical upper CR limit of 0.10. If the calculated CR is greater than 0.10, this empirically indicates excessive intransitivities of preferences (either real intransitivities or inconsistencies in stated degrees of preferences). Normally the CR can be reduced by reassessing preferences [Canada, p. 265 - 284]. The CR in Figure 4 is 0.05. On the basis of Saaty's empirical suggestion that a CR ≤ 0.10 is acceptable, it is concluded that the main attribute pairwise comparisons to obtain attribute weights are reasonably consistent.

	STORAGE	HAZARD	PRO_COST	ENGINE	HANDLING	FACILITY	Sum	Weight
STORAGE	0.069	0.038	0.125	0.085	0.133	0.042	0.492	0.082
HAZARD	0.207	0.115	0.188	0.106	0.133	0.083	0.832	0.139
PRO_COST	0.034	0.038	0.063	0.106	0.067	0.042	0.349	0.058
ENGINE	0.345	0.462	0.250	0.423	0.400	0.500	2.379	0.396
HANDLING	0.069	0.115	0.125	0.141	0.133	0.167	0.750	0.125
FACILITY	0.276	0.231	0.250	0.141	0.133	0.167	1.197	0.200
Total	1.000	1.000	1.000	1.000	1.000	1.000		1.000
							CR = 0.05	

Figure 4. Normalized preference comparisons with respect to the focus objective and main attribute weights

The decision maker assessed the importance of each subattribute to be equal relative to its parent attribute. For example the subattributes Cost (ENG_COST), Risk (RISK), and Capabilities (CAPABIL) under the parent attribute RCS Engine Development (ENGINE) have a priority weight of 1/3 each.

Figures 5, 6, 7, 9, 10, 11, 12, 14, 15, and 16 describe the decision maker's pairwise preferences for each of the two propellant alternatives with respect to the various attributes. Figures 8, 13, and 17 consolidate alternative ratings with respect to child attributes to develop ratings with respect to the parent (main) attributes. Figure 18 consolidates alternative ratings with respect to main attributes into overall alternative scores with respect to the goal.

GOAL > STORAGE	N2O4/MMH	H2O2/RP1	N2O4/MMH	H2O2/RP1	Sum	Weight
N2O4/MMH	1	5	0.833	0.833	1.667	0.833
H2O2/RP1	1/5	1	0.167	0.167	0.333	0.167
Total	1.200	6.000	1.000	1.000		1.000

Figure 5. Preference comparisons and calculation of priority weights with respect to STORAGE goal

GOAL > HAZARD > HEALTH	N2O4/MMH	H2O2/RP1	N2O4/MMH	H2O2/RP1	Sum	Weight
N2O4/MMH	1	1/4	0.200	0.200	0.400	0.200
H2O2/RP1	4	1	0.800	0.800	1.600	0.800
Total	5.000	1.250	1.000	1.000		1.000

Figure 6. Preference comparisons and calculation of priority weights with respect to HAZARD > HEALTH goal

GOAL > HAZARD > EXPLOSIV	N2O4/MMH	H2O2/RP1	N2O4/MMH	H2O2/RP1	Sum	Weight
N2O4/MMH	1	1/3	0.250	0.250	0.500	0.250
H2O2/RP1	3	1	0.750	0.750	1.500	0.750
Total	4.000	1.333	1.000	1.000		1.000

Figure 7. Preference comparisons and calculation of priority weights with respect to HAZARD > EXPLOSIVE goal

GOAL > HAZARD	HEALTH	EXPLOSIV	Weight
N2O4/MMH	0.100	0.125	0.225
H2O2/RP1	0.400	0.375	0.775
Total			1.000

Figure 8. Calculation of priority weights with respect to HAZARD goal

GOAL > PRO_COST	N2O4/MMH	H2O2/RP1	N2O4/MMH	H2O2/RP1	Sum	Weight
N2O4/MMH	1	5	0.833	0.833	1.667	0.833
H2O2/RP1	1/5	1	0.167	0.167	0.333	0.167
Total	1.200	6.000	1.000	1.000		1.000

Figure 9. Preference comparisons and calculation of priority weights with respect to PRO_COST goal

GOAL > ENGINE > ENG_COST	N2O4/MMH	H2O2/RP1	N2O4/MMH	H2O2/RP1	Sum	Weight
N2O4/MMH	1	7	0.875	0.875	1.750	0.875
H2O2/RP1	1/7	1	0.125	0.125	0.250	0.125
Total	1.143	8.000	1.000	1.000		1.000

Figure 10. Preference comparisons and calculation of priority weights with respect to ENGINE > ENG_COST goal

GOAL > ENGINE > RISK	N2O4/MMH	H2O2/RP1	N2O4/MMH	H2O2/RP1	Sum	Weight
N2O4/MMH	1	3	0.750	0.750	1.500	0.750
H2O2/RP1	1/3	1	0.250	0.250	0.500	0.250
Total	1.333	4.000	1.000	1.000		1.000

Figure 11. Preference comparisons and calculation of priority weights with respect to ENGINE > RISK goal

GOAL > ENGINE > CAPABIL	N2O4/MMH	H2O2/RP1	N2O4/MMH	H2O2/RP1	Sum	Weight
N2O4/MMH	1	1	0.500	0.500	1.000	0.500
H2O2/RP1	1	1	0.500	0.500	1.000	0.500
Total	2.000	2.000	1.000	1.000		1.000

Figure 12. Preference comparisons and calculation of priority weights with respect to ENGINE > CAPABIL goal

GOAL > ENGINE	ENG_COST	RISK	CAPABIL	Weight
N2O4/MMH	0.292	0.250	0.167	0.708
H2O2/RP1	0.042	0.083	0.167	0.292
Total				1.000

Figure 13. Calculation of priority weights with respect to ENGINE goal

GOAL > HANDLING	N2O4/MMH	H2O2/RP1	N2O4/MMH	H2O2/RP1	Sum	Weight
N2O4/MMH	1	1/4	0.200	0.200	0.400	0.200
H2O2/RP1	4	1	0.800	0.800	1.600	0.800
Total	5.000	1.250	1.000	1.000		1.000

Figure 14. Preference comparisons and calculation of priority weights with respect to HANDLING goal

GOAL > FACILITY > COST/SAV	N2O4/MMH	H2O2/RP1	N2O4/MMH	H2O2/RP1	Sum	Weight
N2O4/MMH	1	1/2	0.333	0.333	0.667	0.333
H2O2/RP1	2	1	0.667	0.667	1.333	0.667
Total	3.000	1.500	1.000	1.000		1.000

Figure 15. Preference comparisons and calculation of priority weights with respect to FACILITY > COST/SAV goal

GOAL > FACILITY > SRL_PRCS	N2O4/MMH	H2O2/RP1	N2O4/MMH	H2O2/RP1	Sum	Weight
N2O4/MMH	1	1/3	0.250	0.250	0.500	0.250
H2O2/RP1	3	1	0.750	0.750	1.500	0.750
Total	4.000	1.333	1.000	1.000		1.000

Figure 16. Preference comparisons and calculation of priority weights with respect to FACILITY > SRL_PRCS goal

GOAL > FACILITY	COST/SAV	SRL_PRCS	Weight
N2O4/MMH	0.167	0.125	0.292
H2O2/RP1	0.334	0.375	0.709
Total			1.000

Figure 17. Calculation of priority weights with respect to FACILITY goal

GOAL > Best Alternative	STORAGE	HAZARD	PRO_COST	ENGINE	HANDLING	FACILITY	Weight
N2O4/MMH	0.068	0.031	0.048	0.280	0.025	0.058	0.512
H2O2/RP1	0.014	0.108	0.010	0.116	0.100	0.142	0.489
Total							1.000

Figure 18. Calculation of the alternative priority weights

The overall (global) alternative scores, shown in Figure 18, are 0.512 versus 0.489 in favor of the N_2O_4/MMH (hypergolic) propellant alternative.

Results and Conclusions

The results of this trade study indicate a slight preference for using N_2O_4/MMH hypergolic propellant for the proposed RCS. The advantages in engine development cost and risk (the proposed RCS is based on the existing Space Shuttle design) and in the capability for easy storage seemed to more than overcome the disadvantages in hazard potential, handling and transportation requirements, and facility impacts. Propellant procurement was judged strongly in favor of the N_2O_4/MMH alternative because H_2O_2 is no longer manufactured at a rocket propellant grade; therefore a source for propellant grade H_2O_2 would have to be developed.

The AHP model input in this trade study was interpreted and consolidated by the decision maker based on responses obtained after questioning several domain experts. The results of this study are close enough to warrant further investigation. A recommendation for further study is to have several engineers and analysts, whom are experts in different aspects of space transportation vehicle processing and propellant systems servicing, make the same pairwise comparisons used for the AHP in this study and then average their judgments. The proper averaging method is the geometric mean. If $a_{ij,1}, a_{ij,2}, \ldots, a_{ij,n}$ represent the different judgments of the n members, the composite judgment is given by [Harker, p. 18]:

$$a_{ij,avg} = [a_{ij,1} \times a_{ij,2} \times \ldots \times a_{ij,n}]^{(1/n)}.$$

Value Assessment of the Analytic Hierarchy Process in this Decision Situation

The AHP, with the support of the *Expert Choice* software application program, helped this decision making process by modeling the problem in a manageable structure. This arrangement made it possible to focus on each and every part of the problem, and to derive local priorities from simple pairwise comparisons based on the decision maker's experience. A synthesis of the local priorities resulted in the overall (global) priorities for the alternatives. The documentation produced in this report serves as an excellent vehicle for communicating and justifying the recommended decision.

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