THE APPLICATION OF A TRADE STUDY METHODOLOGY TO DETERMINE WHICH CAPABILITIES TO IMPLEMENT IN A TEST FACILITY DATA ACQUISITION SYSTEM UPGRADE

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Abstract

More and more test programs are requiring high frequency measurements. Marshall Space Flight Center's Cold Flow Test Facility has an interest in acquiring such data. The acquisition of this data requires special hardware and capabilities. This document provides a structured trade study approach for determining which additional capabilities of a VXI-based data acquisition system should be utilized to meet the test facility objectives. The paper is focused on the trade study approach detailing and demonstrating the methodology. A case is presented in which a trade study was initially performed to provide a recommendation for the data system capabilities. Implementation details of the recommended alternative are briefly provided as well as the system's performance during a subsequent test program. The paper then addresses revisiting the trade study with modified alternatives and attributes to address issues that arose during the subsequent test program. Although the model does not identify a single best alternative for all sensitivities, the trade study process does provide a much better understanding. This better understanding makes it possible to confidently recommend Alternative 3 as the preferred alternative.

Acronyms

CADDMAS......Computer Aided Dynamic Data Monitoring and Analysis System

DAS.................Data Acquisition System

MSFC...............Marshall Space Flight Center

NASA................National Aeronautics and Space Administration

SMART............Simple Multi-Attribute Rating Technique

VXI..................Versa Module Eurocard eXtensions for Instrumentation

Background

Human spaceflight is one of the most complex sociopolitical, scientific and engineering undertakings of all times. Sending a representative human being from any society to altitudes and distances beyond which few others have traveled says volumes about the society undertaking the feat as well as speaks to those individuals who step forward to contribute. To build spacecraft hardware requires a mastery of the sciences and a progressive engineering approach but to build human spaceflight hardware requires the development of a spacecraft worthy of representing such a society and capable of safely transporting the most precious of payloads.

To date, the only practical propulsion method with sufficient energy for launching spacecraft from Earth and reaching orbital levels has been by combustion of chemical propellants. [1] This method of propulsion results in highly complex systems. [2] The performance requirements and harsh operational environments of these propulsion systems have pushed the design of components to operate near their structural and design limits. To mitigate these margins, experimental tests are used to assist in the definition of complicated three-dimensional flow environments as well as to determine hardware performance.

During the late 1990's, a test program was conducted at NASA's Marshall Space Flight Center's (MSFC) Cold Flow Test Facility. The primary purpose of that test program was to increase the understanding of dynamic environments in turbines. The program involved developing a full-scale cold flow turbine model and instrumenting the rotor blades with surface-mounted high frequency pressure transducers. [3] The data for the test was monitored and collected with the Computer Aided Dynamic Data Monitoring and Analysis System (CADDMAS). [4] The CADDMAS was, at the time, one of the first real-time data monitoring and acquisition systems. This program resulted in many improvements to testing as well as the monitoring and acquisition of high frequency measurements.

Introduction

Data acquisition hardware has improved significantly over the last decade. To maintain a high level of capability, MSFC's Cold Flow Test Facility upgraded its dynamic data monitoring and recording system from the previously used CADDMAS to a VXI-based system. The monitoring and recording capabilities of the system had been used to monitor and record high frequency measurements on two previous test programs. In both programs, the VXI system had proven to be a reliable replacement for the monitoring and acquisition capabilities of the previous CADDMAS system. Once the VXI-based system's base monitoring and recording capabilities had been proven it was decided to perform a trade study to explore which, if any, additional capabilities of the VXI system should be utilized.

The purpose of this paper is to present a case in which a trade study approach was initially performed to provide a requisite, or sufficiently analyzed, recommendation for which a decision could be made. [5] The paper continues by discussing the implementation of the chosen alternative and the system's performance during a subsequent test program. Finally, the paper then documents revisiting the trade study with modified alternatives and attributes to address issues that arose during the subsequent test program.

Trade Study Methodology

A deviation of the SMART (Simple Multi-attribute Rating Technique) methodology was utilized for the trade study. Input was taken from Systems Engineering Principles and Practice [7] to modify the eight original steps for a SMART analysis, detailed in Goodwin and Wright. [6] These modifications provide additional steps to further clarify the process. The general steps are enumerated below:

1. Identify decision maker(s).
2. Define objective(s).
3. Determine alternatives.
4. Identify the relevant attributes.
5. Assign metrics to the attributes.
6. Determine a weight for each attribute.
7. Assign values ratings for alternatives.
8. Calculate the comparative scores.
9. Make a provisional decision.
10. Perform sensitivity analysis.
11. Make a requisite recommendation.

The following sections follow these general steps for evaluation of the data acquisition system trade.

Objectives and Attributes

The VXI system had already demonstrated effectiveness in meeting the data monitoring and recording requirements for the test facility. The objectives for the trade study were developed through discussions with the test conductors and data analysts. The objectives were to determine which VXI system configuration would result in the simplest, most reliable, and least intrusive system that would continue to meet the test facility's needs.

In order to reduce the teams time spent in a conference room, the systems engineer developed the attributes, subattributes, and subattribute measures with minimal team participation. The following attributes were selected to measure the performance of each alternative to meet the above stated objectives:

Attribute 1. Complexity attributes mapped back to the "simplicity" objective and included the following subattributes:
- a. Number of subsystems
- b. Complexity of subsystems
- c. Number of interfaces
- d. Skill level required to setup

Attribute 2. Reliability attribute mapped back to the "reliable" objective and included the number of failures per eight hours of testing.

Attribute 3. Replacement attributes mapped back to the "reliable" objective and includes the following subattributes:
- a. Cost to replace/repair one channel
- b. Time required to replace/repair one channel

Attribute 4. Setup mapped back to the "least intrusive" objective and includes the following subattributes:
- a. Cost and hours for initial setup
- b. Cost and hours for test series setup
- c. Cost and hours for daily setup.

Attribute 5. Safety is innate in all test hardware and is mapped back to meeting test needs. This includes possible hazards to personnel and/or hardware.

After the attributes were developed, a detailed explanation of the attributes and how they address the facility's objectives was presented to the team members for input and discussion. To assist the discussion, it was necessary to have a general concept of the alternatives in order to discuss how these attributes could be used to distinguish the alternatives.

At this point, the standard SMART methodology would call for using swing weight to develop the attribute weights. This analysis deviated from the use of swing weights and opted for the use of pairwise comparisons to weight the attributes. This choice was made primarily because of the number of team members and the simplicity of talking through only one matrix with all members. [7] The pairwise matrix shown in Exhibit 1 was formed by having a team discussion and comparing the relative importance of all attributes. The development of this matrix identified the value structure of the team. The pairwise matrix results were weighted using a rank sum method to develop the attribute weights. See Exhibit 2 for the rank sum results.

While discussing the attributes with the team, it was determined that in-category weighting would be preferred rather than equally weighting each subattribute within their respective higher level attribute. For example, the Setup attribute was comprised of three subattributes: Initial Setup, Test Series Setup, and Daily Setup. While all are important and would be accounted for, the Initial Setup and Test Setup are performed much less frequently than Daily Setup. A Daily Setup may be performed 100 times compared to one time for the Initial and Test Series setups. It would hardly make sense to weight these equally. This led to the decision to weight subattributes as a percentage of the respective attribute, as shown in Exhibit 5.

Concerns were voiced as to the particular values used for the subattributes weights. This was addressed by reminding team members of the original objectives as well as noting that a sensitivity analysis would determine the robustness of the final recommendation to these subattribute weights.

Exhibit 1. Pairwise Comparison of Attributes

Attributes		A Complexity	B Reliability	C Replacement	D Safety	E Setup
Complexity	A	-	B	A	D	A
Reliability	B		-	B	D	B
Replacement	C			-	D	E
Safety	D				-	D
Setup	E					-

Exhibit 2. Attributes, Ranks, and Weights.

Attribute	Rank	Inverted Rank	Weight
1) Complexity a. Minimize number of subsystems b. Minimize complexity of subsystems ranked versus other alternatives c. Minimize number of interfaces d. Minimize skill level required to setup and use	3	3	20%
2) Reliability a. Minimize number of failures per eight hours of testing	2	4	27%
3) Replacement a. Minimize cost to replace/repair one channel b. Minimize time required to replace/repair one channel	5	1	7%
4) Safety a. Minimize possible hazards to people and hardware	4	2	33%
5) Setup a. Minimize cost and hours for initial setup b. Minimize cost and hours for test series c. Minimize setup cost and hours for daily setup	1	5	13%

Alternatives

Three hardware alternatives were selected for scoring. Alternative 1 utilized no additional capabilities and continued using the system as a data monitoring and recording system only. Alternative 2 continued using the data monitoring and recording capabilities as well as the signal conditioning capabilities. Finally, Alternative 3 continued using the data monitoring and recording capabilities as well as the signal conditioning and dedicated power supply capabilities.

These alternatives are detailed below and illustrated in Exhibit 3.

Alternative 1. Utilized no additional capabilities

a. Amplifier provides transducer excitation voltage
b. Transducer converts physical phenomena to a measurable quantity (voltage)
c. Amplifier provides signal conditioning – filtering, gain, coupling, and isolation between transducer and DAS (data acquisition system)
d. The DAS records data and allows real time monitoring of signal
e. Voltage calibration is performed by injecting a calibrated voltage at second amplifier input

Alternative 2. Utilize only signal conditioning capabilities

a. Amplifier provides excitation voltage to power transducer
b. Transducer converts physical phenomena to a measurable quantity (voltage)
c. The DAS conditions the signal, records data and allows real time monitoring of signal

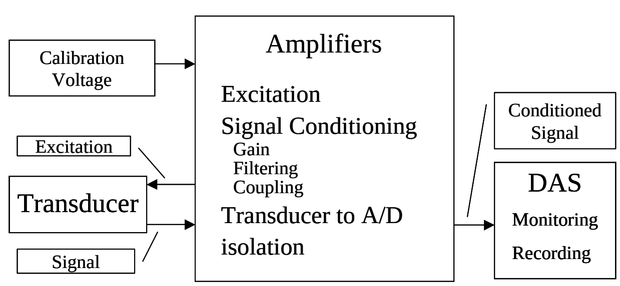
Alternative 3. Utilize both signal conditioning and power supply capabilities

a. Dedicated power supply provides excitation voltage to power transducer
b. Transducer converts physical phenomena to a measurable quantity (voltage)
c. The DAS conditions the signal, records data and allows real time monitoring of signal

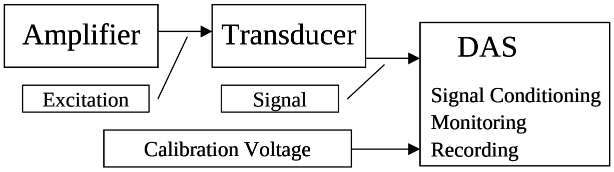
Additional alternatives could have been generated by considering the many software capabilities that the VXI system has to offer. The team decided not to incorporate software alternatives because of the extremely large number of possible configurations and the fact that most foreseeable software modifications would not result in significant changes to the facility and therefore could be considered with much less rigor at a later time.

Exhibit 3. Alternatives

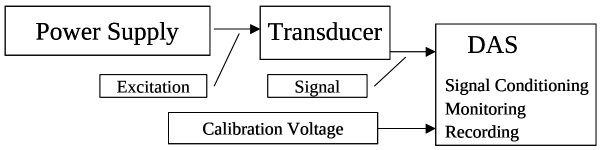
Alternative 1 - Utilize no additional capabilities.



Alternative 2 - Utilize only signal conditioning capabilities.



Alternative 3 – Utilize both signal conditioning and power supply capabilities.



Scoring the Alternatives

The systems engineer initially scored each alternative on all attributes detailed in the Objectives and Attributes section. A narrative evaluation was provided to the team for discussion and inputs. The team inputs were incorporated and are detailed in Exhibit 4.

All evaluations were based on quantitative measures with the exception of the "Complexity of Subsystems" and the "Skill level required to setup and use" subattributes. These subattributes were scored by the team based on the relative complexity of each alternative. All evaluations were then converted to a five-point scale with 5 being the best and 1 being the worst. The equivalent numeric evaluation of Exhibit 4 is shown in Exhibit 5.

It should be noted that all alternatives had equal rank on the following subattributes: Test Series Setup Costs, Daily Setup Costs, and Possible Hazard to People. When all alternatives are scored equally against an attribute that attribute offers no value or utility to the study and can then be thrown out. [6] That being stated, these subattributes were carried through the rest of the study but did not contribute to the final decision.

Calculations to Make a Selection

The final scores were calculated in two steps. The first step was to calculate attribute scores. This was done by summing, within each attribute group, the products of each alternative's score and the corresponding subattribute weights. Next, for each alternative, these attribute scores were multiplied by their corresponding attribute weights and summed for a final score.

The attribute scores are denoted in Exhibit 5 with a single underline. A sample attribute score calculation for the Complexity Attribute of Alternative 1 is shown in Equation (1) below.

$$(0.2*3)+(0.2*1)+(0.2*3)+(0.4*1) = \underline{1.8} \qquad (1)$$

The final scores are denoted in Exhibit 5 with a double underline. A sample final score calculation for the overall score of Alternative 1 is shown in Equation (2).

$$(0.2*1.8)+(0.27*1)+(0.07*4.5)+(0.13*2.5)+(0.33*4.8) = \underline{\underline{2.86}} \qquad (2)$$

The final scores are shown in Exhibit 5. Of the three alternatives, the 4.15 value is highest and therefore indicated that Alternative 3 - Utilize both signal conditioning and power supply capabilities best meets our values structure and should be chosen.

Exhibit 4. Evaluation of Alternatives

	Alternatives		
Attributes	1	2	3
Complexity			
Number of Subsystems	5 subsystems	4 subsystems	4 subsystems
Complexity of Subsystems	Using all amplifier capabilities is extremely complex	Limiting amplifier use simplifies overall system. Subsystems have more dedicated purposes	All subsystems have a dedicated use
Number of interfaces	4 - cal to amp, amp to transducer, transducer to amp, amp to DAS	3 – cal to DAS, amp to transducer, transducer to DAS	3 - cal to DAS, power supply to transducer, transducer to DAS
Skill level required to setup and use (scale 1 to 5)	5 - requires in-depth knowledge of 5 subsystems and 4 interfaces	3 - requires knowledge of 4 subsystems and 3 interfaces	2 - requires knowledge of 3 subsystems and 4 interfaces but the power supply is less involved than the amplifier
Reliability			
Number of failures per 8 hours of testing	0.4 - 2 failures per 5 days	0.1 - 1 failure per 10 days	0.05 - 1 failure per 20 days
Replacement			
Cost to replace/repair 1 channel	$3200 - 1 amp, 1/16 DAS board, 1 transducer, 1/80 calibration source	$3200 - 1 amp, 1/16 DAS board, 1 transducer, 1/80 calibration source	$2400 - 1/16 power supply, 1/16 DAS board, 1 transducer, 1/80 calibration source
Time required to replace/repair 1 channel	1 minute - transducer has 1 connector and amps are individually replaceable	2 minutes - transducer has 2 connectors and amps are individually replaceable	30 minutes - transducer has 2 connectors and power supply requires 16 channels being changed at once
Safety			
Possible hazard to people	Negligible (or alternative would not be considered)	Negligible (or alternative would not be considered)	Negligible (or alternative would not be considered)
Possible hazard to hardware	Low - Amplifiers provide isolation to DAS	Medium - DAS has limited signal isolation	Medium - DAS has limited signal isolation
Setup			
Initial Setup			
Hours	0 - currently installed	120 hours - requires 1 additional set of cables because excitation and signal cables will be separate as well as building a new calibration interface	120 hours - requires 1 additional set of cables because excitation and signal cables will be separate as well as building a new calibration interface
Cost	0 - currently installed	$50,000 - $24,000 for two spare DAS boards +26,000 for new cabling and calibration interface	$94,800 - $24,000 for two spare DAS boards +26,000 for new cabling and calibration interface+ 44,800 for power supplies
Test Series Setup			
Hours	48 hours - 2 days to route cables, 1 day for amp setup and 3 days to perform checkouts	64 hours - 4 days to route cables, 1 day for amp setup and 3 days to perform checkouts (twice as many cables to run)	56 hours - 4 days to route cables and 3 days to perform checkouts (twice as many cables to run)
Cost	Negligible	Negligible	Negligible
Daily Setup			
Hours	60 minutes - to perform calibrations with amps	5 minutes - amps no longer influence cals	5 minutes - amps no longer influence cals
Cost	Negligible	Negligible	Negligible

Exhibit 5. Scoring of Alternatives

Attributes	Subattribute Weights	Attribute Weights	Alternatives 1	2	3
Complexity	Σ1	0.20	1.8	3.4	4.2
Number of Subsystems	0.2		3	4	4
Complexity of Subsystems	0.2		1	3	5
Number of interfaces	0.2		3	4	4
Skill level required to setup and use (scale 1 to 5)	0.4		1	3	4
Reliability	Σ1	0.27	1	3	5
Number of failures per 8 hours of testing	1		1	3	5
Replacement	Σ1	0.07	4.5	4.5	2.5
Cost to replace/repair 1 channel	0.25		3	3	4
Time required to replace/repair 1 channel	0.75		5	5	2
Safety	Σ1	0.33	4.8	3.9	3.9
Possible hazard to people	0.1		3	3	3
Possible hazard to hardware	0.9		5	4	4
Setup	Σ1	0.13	2.5	3.9	3.8
Initial Setup					
Hours	0.1		5	3	3
Cost	0.1		5	3	1
Test Series Setup					
Hours	0.1		4	2	3
Cost	0.1		3	3	3
Daily Setup					
Hours	0.5		1	5	5
Cost	0.1		3	3	3
			2.86	**3.60**	**4.15**

Sensitivity

To determine our confidence in the value of our selection, a sensitivity analysis was performed. Three approaches were considered for the sensitivity analysis. The first approach considered reevaluating the rank and weights of the five chosen attributes. The second approach considered reevaluating the subattribute weights. The third approach considered reevaluating each alternative's score.

The team decided there was no interest in reevaluating the scores for each alternative because the initial scores were primarily quantitative and were considered to be accurate and representative. However, the team decided to investigate the effects of modifying the five attribute weights and the subattribute weights. Modifying the attribute and subattribute weights would assist in determining if Alternative 3 would still be the preferred alternative if the value structure changed.

Sensitivity Approach 1 - Modifying Attribute Weights

When considering modifying the attribute weights, it was noted that Safety was initially weighted the highest of all attributes and that Reliability was initially weighted second of the attributes. These initial weightings were based on the test needs objective which includes the value that no unscheduled downtime would be acceptable, either due to failure or damage. What if the team were willing to trade both Hardware Safety and Reliability for both Replacement and Complexity with the preference given to Replacement? Exhibit 6 shows the modified pairwise comparison matrix.

This change in weighting essentially means that the team would be less stringent on damage and failure if it were possible to make repairs or replacements quickly. This only slightly modified our value from "no downtime" to "limited downtime" and resulted in slightly favoring Alternative 2. Exhibit 7 shows the modified final scores. These results add confidence to the Alternative 2 recommendation by not strongly favoring another alternative.

Exhibit 6. Pairwise Comparison of Attributes with Modified Attribute Weights

Attributes		A Complexity	B Reliability	C Replacement	D Safety	E Setup
Complexity	A	-	A	C	A	A
Reliability	B		-	C	D	B
Replacement	C			-	C	E
Safety	D				-	D
Setup	E					-

Exhibit 7. Sensitivity Approach 1 Result.

Attribute	Rank	Inverted Rank	Weight	Alternatives 1	2	3
Complexity	2	4	0.267	0.48	0.91	1.12
Reliability	4	2	0.133	0.13	0.40	0.67
Replacement	2	4	0.267	1.20	1.20	0.67
Safety	3	3	0.200	0.96	0.78	0.78
Setup	4	2	0.133	0.33	0.52	0.51
			Total	3.11	3.81	3.74

Sensitivity Approach 2 - Modifying Subattribute Weights

When considering modifying the subattribute weights, it was noted that little weight was given to the Cost subattributes. This was the case because the relative costs of cold flow test elements are small when compared to other test types. However, if funding were reduced these values would surely change. Therefore the change in the Cost subattributes' weights was the focus of the subattribute sensitivity analysis.

This approach to sensitivity analysis only effected the Replacement and Setup attributes because they were the only attributes with the subattribute of Cost. To perform the analysis the previously assigned values for

Costs were tripled and the other subattributes were adjusted to ensure the within attribute percentage remained 100%. The analysis resulted in favoring Alternative 3. Exhibit 8 shows the final scores for the modified subattribute sensitivity analysis and again confidence was added to the Alternative 3 recommendation.

Exhibit 8. Sensitivity Approach 2 Results.

		Alternatives		
Attribute	Weight	1	2	3
Complexity	0.200	0.36	0.68	0.84
Reliability	0.267	0.27	0.80	1.33
Replacement	0.067	0.23	0.23	0.23
Safety	0.333	1.60	1.30	1.30
Setup	0.133	0.48	0.41	0.33
	Total	2.94	3.42	4.04

Initial Recommendation

Upon completion of the trade and sensitivity analysis, it was recommended that the MSFC Cold Flow Test Facility move forward with Alternative 3 which was to begin utilizing both signal conditioning and dedicated power supply capabilities of the VXI-based system. A meeting was held to discuss the recommendation and a presentation was made to describe the necessary changes. During the meeting, a go forward plan was developed for implementing the necessary facility modifications. The spreadsheet used to perform the trade study was beneficial in developing the plan.

Implementation of Alternative 3

The necessary changes were made to the facility and the system over several months. Power supplies were installed. Cables were made and installed. Upon completion of modifications, the system was verified using the facility standards which had been used in the past. All checkouts indicated that the system would perform as expected.

After checkouts and verifications were complete, a test was requested. This test included new instrumentation which had never previously been used on the VXI-based system. Unforeseen issues began to arise. The primary concerns were:

1. A low common mode rejection ratio contributed to a decreased signal to noise ratio.
2. The identification of a facility resonance which required some signals to be notch filtered prior to reaching the data acquisition system.
3. The difficulty of injecting a common signal across all channels simultaneously made the system difficult to troubleshoot.

These issues required the 3rd alternative to be modified resulting in a 4th alternative.

Introducing a 4th Alternative

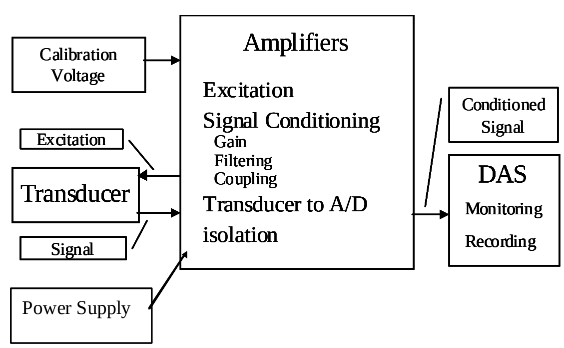
In order to address the problems that arose during the testing, the amplifiers were brought back into the system for the channels which were experiencing the issues. The amplifiers provided a solution to these issues by improving the common mode rejection ratio, having the capability to notch filter around the facility resonance enabling data content above and below the resonant frequency, and to allow for simultaneous signal injection on channels with the amplifiers in place.

While the amplifiers did address the issues, bringing them back into the system greatly diminished the appeal of Alternative 3. Requiring the use of amplifiers resulted in the following alternative description which was called Alternative 4. Exhibit 9 is a diagram of Alternative 4.

Alternative 4. - Utilize both signal conditioning and power supply capabilities as well as amplifiers

a. Dedicated power supply and amplifiers provide excitation voltages to power transducer
b. Transducer converts physical phenomena to a measurable quantity (voltage)
c. Amplifiers can provide signal conditioning
    i. Filtering
    ii. Gain
    iii. Coupling
    iv. Provide isolation
d. The DAS records data and allows real time monitoring of signal
e. Voltage calibration can be performed by injecting a calibrated voltage at second amplifier input

Exhibit 9. Utilize both signal conditioning and power supply capabilities as well as amplifiers



Alternative 4 was essentially Alternative 1 with the addition of external power supplies and new cabling. The implementation of Alternative 3 was no small task. When it became necessary to add amplifiers back into the system, two questions quickly arose: Why didn't the trade study recommend Alternative 1 in the first place and how would Alternative 4 perform in the study.

Scoring Alternative 4

Alternative 4 was added to the trade and the scores were calculated. Exhibit 10 illustrates how poorly Alternative 4 scored. This was no surprise. As was previously stated, Alternative 4 was essentially Alternative 1 with the addition of external power supplies and cabling. During the initial trade, Alternative 1 was rated the lowest and now with the additional complexity and costs as Alternative 4 it scores even lower.

Exhibit 10.Scoring of Alternatives with Alternative 4

Attributes	Subattribute Weights	Attribute Weights	Alternatives 1	2	3	4
Complexity	Σ1	0.20	1.8	3.4	4.2	1.4
Number of Subsystems	0.2		3	4	4	3
Complexity of Subsystems	0.2		1	3	5	1
Number of interfaces	0.2		3	4	4	1
Skill level required to setup and use (scale 1 to 5)	0.4		1	3	4	1
Reliability	Σ1	0.27	1	3	5	3
Number of failures per 8 hours of testing	1		1	3	5	3
Replacement	Σ1	0.07	4.5	4.5	2.5	2.25
Cost to replace/repair 1 channel	0.25		3	3	4	3
Time required to replace/repair 1 channel	0.75		5	5	2	2
Safety	Σ1	0.33	4.8	3.9	3.9	3.9
Possible hazard to people	0.1		3	3	3	3
Possible hazard to hardware	0.9		5	4	4	4
Setup	Σ1	0.13	2.5	3.9	3.8	1.7
Initial Setup						
Hours	0.1		5	3	3	3
Cost	0.1		5	3	1	1
Test Series Setup						
Hours	0.1		4	2	3	2
Cost	0.1		3	3	3	3
Daily Setup						
Hours	0.5		1	5	5	1
Cost	0.1		3	3	3	3
			2.86	**3.60**	**4.15**	**2.76**

The 6th Attribute – Capability

As suggested by Goodwin and Wright, any conflict between the analytic rankings and holistic rankings should be evaluated. This suggests that an important element of the problem has not been captured. [6] Indeed that was the case. When considering the initial objectives the VXI-based system was assumed to have sufficient monitoring and acquisition capabilities and the trade was performed to determine which VXI system configuration would result in the simplest, most reliable, and least intrusive system that would continue to meet the test needs.

The new instrumentation changed all of this. The previous history of success with the VXI-based system was not applicable anymore. Without the additional capabilities of the amplifiers the VXI-based system could no longer meet the test needs. In order to capture this an additional attribute was necessary. That attribute was called Capability and referred to the systems capability of adapting to accommodate future needs.

The trade analysis was repeated to include all four alternatives with the incorporation of the Capability Attribute. Exhibit 11 illustrates the alternative scores as well as the final scores. Alternative 3 was still the slightly preferred solution over Alternatives 4 and 1. This seems impossible because Alternative 3 alone could not meet the objectives. This is the result of the additional trades offs in which Alternative 3 is still the preferred alternative.

In order to develop a better understanding, the same attribute sensitivity study which was performed on the initial trade was again applied for the revised model. In this application, the Capability Attribute was maintained as the primary attribute followed by the Replacement and Complexity attributes. The results shown in Exhibit 12 indicate that unlike the previous model, this model does not indicate Alternative 3 as a clear cut decision. Depending on the value structure chosen Alternatives 1, 3 or 4 may possibly be chosen.

Conclusion and Recommendations

The trade study process outlined in Goodwin and Wright [6] was followed to provide an informed recommendation as to which system capabilities should be utilized. The process was structured and logical and can be followed by those wishing to reproduce it. The original recommendation was based on insufficient attributes developed from inadequate objectives and resulted in a less than desired outcome. The model was modified to address the previous models shortcomings and the new model was still unable to identify a single best alternative. Although the model was unable to identify a single best alternative, the process did provide a much better understanding. That better understanding made it possible to make the recommendation to set the test facility up with the intent to use Alternative 3. Should the need for additional capability be necessary it would then be possible to include only those additional elements which are necessary to meet the test objectives. This approach will utilize the benefits of both Alternatives 3 and 4 while minimizing the drawbacks to Alternative 4.

It should also be noted that without the earlier recommendation for and implementation of Alternative 3 it would not be possible to utilize the benefits because the additional power supplies and cables would not be available.

Exhibit 11. Final Scores with Alternative 4 and Capability Attribute

Attributes	Subattribute Weights	Attribute Weights	Alternatives 1	2	3	4
Capability	Σ1	0.24	4	1	1	5
Addresses changing requirements	1		4	1	1	5
Complexity	Σ1	0.14	1.8	3.4	4.2	1.4
Number of Subsystems	0.2		3	4	4	3
Complexity of Subsystems	0.2		1	3	5	1
Number of interfaces	0.2		3	4	4	1
Skill level required to setup and use (scale 1 to 5)	0.4		1	3	4	1
Reliability	Σ1	0.19	1	3	5	3
Number of failures per 8 hours of testing	1		1	3	5	3
Replacement	Σ1	0.05	3.5	3.5	3.5	2.75
Cost to replace/repair 1 channel	0.75		3	3	4	3
Time required to replace/repair 1 channel	0.25		5	5	2	2
Safety	Σ1	0.29	4.8	3.9	3.9	3.9
Possible hazard to people	0.1		3	3	3	3
Possible hazard to hardware	0.90		5	4	4	4
Setup	Σ1	0.10	2.5	3.9	3.8	1.7
Initial Setup						
Hours	0.1		5	3	3	3
Cost	0.1		5	3	1	1
Test Series Setup						
Hours	0.1		4	2	3	2
Cost	0.1		3	3	3	3
Daily Setup						
Hours	0.5		1	5	5	1
Cost	0.1		3	3	3	3
			3.18	2.95	3.43	3.37

Exhibit 12. Sensitivity Analysis to Attribute Ranks

Attribute	Rank	Inverted Rank	Weight	Alternatives 1	2	3	4
Capability	1	6	0.29	1.14	0.29	0.29	1.43
Complexity	3	4	0.19	0.34	0.65	0.80	0.27
Reliability	5	2	0.10	0.10	0.29	0.48	0.29
Replacement	2	5	0.24	0.83	0.83	0.83	0.65
Safety	4	3	0.14	0.12	0.19	0.18	0.08
Setup	6	1	0.05	0.69	0.56	0.56	0.56
			Total	3.22	2.80	3.13	3.27

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