STAKEHOLDER VALUE DRIVEN SPACE MISSION ARCHITECTURE TRADE OFF

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Abstract. *One the most difficult aspects of system conceptualization process is to recognize, understand and manage the trade-offs to maximize the success of the product. This is particularly important for space project development that requires a high level of sustainability. Thus, a major part of the system engineer's role is to provide information that the system manager can use to make the right decisions. This includes identification of alternative architectures and characterization of those elements in a way that helps managers to find out, among the alternatives, a design that provides attributes value to stakeholder. Space mission architecture consists of a broad system concept which is the most fundamental statement of how the mission will be carried out and satisfy the stakeholders. The architecture development process starts with the stakeholder analysis which enables the identification of the decision drivers, then, the requirements are analysed for elaborating the system concept. Effectiveness attributes such as performance, cost, risk and schedule are the outcomes of the stakeholder analysis labelled as decision drivers to be used in a trade off process to improve the managerial space mission decisions. The proposal presented herein provides a means for innovating the mission design process by identifying drivers through stakeholder analysis and use them in a trade off process to obtain the stakeholder satisfaction with effectiveness attribute parameters.*

Keywords*: stakeholder, value, trade off, architecture, space mission*

1. INTRODUCTION

Most of the major system decisions (requirements, constrains, system architecture, etc.) are made during the early phases of the project. Part of this work is done during the space mission architecture trade off.

Traditionally, the main objective of space mission architecture trade offs is to meet high performance requirements on a cost-time effective way with low level of risk. It assumes that the stakeholder reasoning is: high performance at low cost and risk within a given schedule. However, stakeholder may value performance, cost, risk and schedule attributes differently. Being so, for the definition of a space mission architecture one must trade-off the amount of value stakeholders relate to cost, performance, risk and schedule attributes rather than trading –off performance, cost, risk and schedule attributes. We propose that they should be traded off against the amount of value stakeholders associate to each of these attributes.

In the literature there are a lot of discussions about how to trade off cost, performance, schedule and risk attributes for systems architecting. “Fortescue and Stark (1995)” discuss the process for generic missions; “Przemieniecki (1993, 1994)” does so for defense missions; and “Shinko (1995)” provides an excellent overview for NASA missions. However there are none that tackles analysis for designing effective architectures in the stakeholder point of view.

Space mission development requires a high level of sustainability that only can be given by stakeholders who provide financial, political, and economic support. Sustainability here refers to the fact that stakeholders will be assured to receive the required amount of value over a specified period of time. In this way, early stage design provides the greatest opportunity to explore design alternatives and perform trade studies to get stakeholder satisfaction.

Thus, an innovative method and a powerful tool are proposed in this paper that is intended for investigating the system trade-off space at an early design phase taking into account stakeholder value.

This work is organized in three core sections, as follows. Section 2 explores the traditional architecture concept process; Section 3 introduces the stakeholder value architecture trade off approach where the following items are discussed: stakeholder and requirement analysis, definition of mission architecture elements and alternative options, identification of decision drivers for each architecture element, defining attribute value weight to stakeholders, stakeholder value trade off matrix and definition of selection rule and decision. Finally, Section 4 poses the method contribution: this is presented by analyzing the trade off architecture of the Apollo and today`s Moon Exploration missions.

2. TRADITIONAL ARCHITECTURE CONCEPT EXPLORATION

Project planning for space products is usually structured into sequential phases. Usually, a project is broken down into seven or six phases according to the NASA or ESA approaches, respectively.

The initial design activity performed by "Advanced Projects" teams consists of inventing, creating, concocting and/or devising a broad spectrum of ideas and alternatives for missions where new projects (programs) could be selected from (Shinko, 1995). Typically, this activity consists of loosely structured examinations of new ideas, usually without central control and mostly oriented towards small studies. Its major product is a stream of suggested projects based on needs capabilities, priorities and resources. The team's effort focuses also on analyzing the project space and establishing a mission architecture. Essentially, all space projects go through mission evaluation and analysis stages many times, so the process presented in “Fig. 1” turns into a spiral i. e. with successive refinements. This process represents the traditional space mission architecture concept exploration.

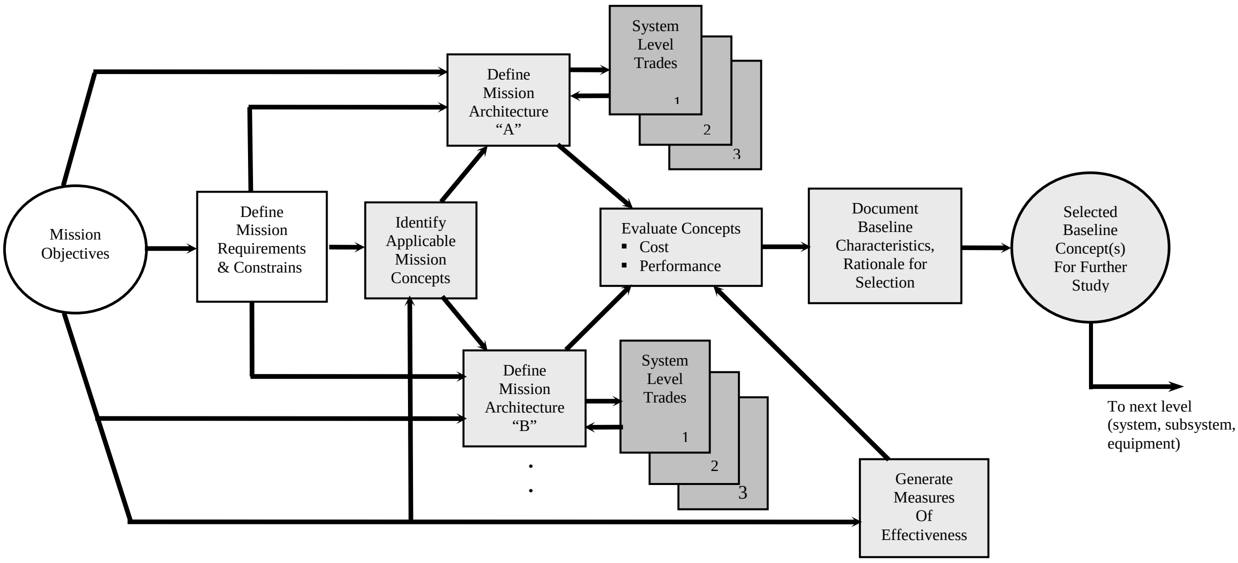

Figure 1. Architecture concept exploration flow (Larson, and Wertz, eds. 2003).

The realization of a system over its life cycle results from a sequence of decisions among several courses of action. If the alternative actions are well differentiated in the effectiveness space, then the system manager can make choices with confidence.

In this way, design trade studies become an important part of the systems engineering process. When the starting point of a design trade study is inside one envelope, there are alternatives that reduce costs without decreasing any aspect of effectiveness or increase some aspects of effectiveness without decreasing others and without increasing costs. Then, the system manager's or system engineer's decision is easy. When the alternatives in a design trade study, however, require trading cost for effectiveness, or even one dimension of effectiveness for another at the same cost the decisions become harder. In this context, risk and schedule behave like a kind of cost (Shinko, 1995). This is a dilemma for system engineers. At the beginning, trade studies start with an assessment of how well each of the design alternatives meets the system effectiveness (performance, cost, schedule, and risk). The ability to perform these studies is enhanced by the development of system models that relate the decision drivers to those assessments. This demonstrates the traditional focus of space mission architecture trade-offs.

3. STAKEHOLDER VALUE ARCHITECTURE TRADE OFF APPROACH

The objective of systems engineering is to derive, develop and verify a life cycle balanced solution that satisfy stakeholders requirements (IEEE-Std 1220, 1994). Stakeholders values are expressed in terms of performance, cost, schedule, and risk attributes which represents system effectiveness. It is proposed herein that the amount of value stakeholders relate to each of these values is the basis for decision making.

Taking into account the statement above and considering that about 80% of the life cycle cost, performance, risk and schedule of a project are committed by decisions made during design concept exploration; this paper addresses several questions such as: how to improve such decisions? How to evaluate system architecture through how much stakeholders value cost, performance, risk and schedule system attributes? How to anticipate such evaluation to the beginning of design process? How to establish the connection between stakeholder values with the architecture elements? These questions do reflect the state of art of the design trade off process regarding to conceptual phase.

Systems exist to generate value to their stakeholders. Unfortunately, this ideal is often met only to a limited degree. Usually, the system manager must choose among designs that differ in terms of numerous value attributes. Often, however, the attributes seem to be truly incommensurate; managers must make their decisions in spite of this multiplicity.

"Figure 2" shows the stakeholder value architecture trade off process in simple terms.

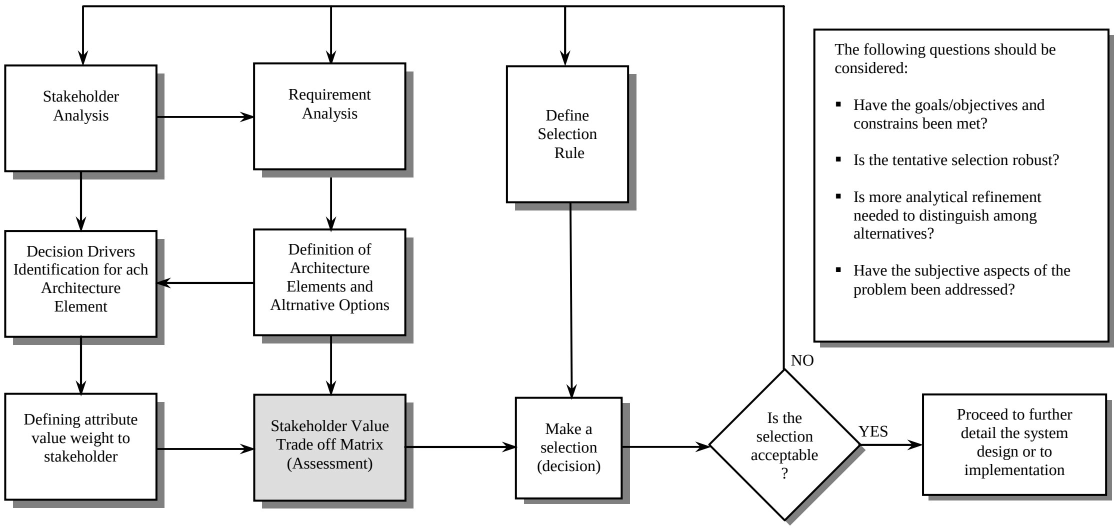

Figure 2. Stakeholder value architecture trade off process

The process begins with the stakeholder analysis where it is defined all interests towards the system to be developed. The requirement analysis (step 1) can be done in the same feedback loop as stakeholder analysis (step 2). Then, architecture elements and their alternatives can be identified (step 3). The definition of key trades for each architecture elements is a creative step where a set of effective solutions can be found. One critical point of this approach is to identify a set of decision drivers that models the architecture attributes for each element (step 4). Then, the method establishes a connection between physical solution and the associated characteristics that can commit cost, performance, risk and schedule in a project. The connections among the stakeholder values and decision drivers are stablished in the attribute value weight (step 5). This step is responsible to define the amount of value stakeholders associate to each of these element attributes (decision driver). The Comprising all these steps, the evaluation of architecture alternatives can be done, assessing element attribute impact on architecture taking into account the attribute value weight to stakeholder identified earlier (step 6). A set of alternatives is evaluated and the selection can be done. If the selection is acceptable (step 9), then proceed to further detail the system design or to implementation Step 10). In opposite the process may require a new stakeholder analysis, requirement analysis or a new selection rule (step 7).

3.1. Stakeholder and Requirement analysis

The section outlines a simple stakeholder and requirement analysis approach. Time spent doing these analyses should match project type and complexity.

The first step is to identify project stakeholders. To be classified as a stakeholder, the person or group must have some interest in the project and its results or a level of influence that can impact the project (Smith, 2000). Stakeholder interests must be understood and so are the potential project impacts if a need is not met. "Figure 3" depicts an example of this high-level analysis. Examples of typical stakeholders are: sponsors, clients, managers and employees.

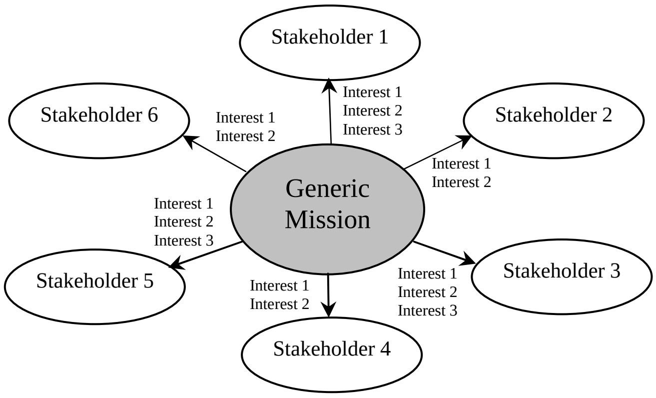

Figure 3. Stakeholder context diagram and interests for a Generic Mission

The second step of the method is to identify the stakeholders' interests and the relative importance (W) for each one. To accomplish this stage, stakeholders should be listed on a table or spreadsheet with their key interests and relative importance (W) in terms of cost, performance, schedule and risk as presented in "Tab.1". A relative importance for stakeholder value (performance-WP, cost-WC, risk-WR and schedule-WS) must be established as reference to identify the value give by stakeholders relates these attributes. Special attention must be paid to outline multiple interests, particularly those that are overt and hidden in relation to project objectives. It is important to keep in mind that identifying interests is done with stakeholders' perspective in mind, not your own.

Table 1. Stakeholder value attributes and importance (W) for a generic mission.

Stakeholder	**Performance (WP=%)**		**Cost (WC=%)**		**Risk (WR=%)**		**Schedule (WS=%)**	
	Interests (values)	**W (%)**	**Interests (values)**	**W (%)**	**Interests (values)**	**W (%)**	**Interests (values)**	**W (%)**
Stakeholder 1	Interest 1	5	Interest 3	3	-	-	Interest 4	7
	Interest 2	10						
Stakeholder 2	Interest 1	7	-	-	Interest 2	5		
Stakeholder 3	Interest 1	5	Interest 2	10	Interest 3	10	Interest 4	5
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
	Total W (%)	100	Total W (%)	100	Total W (%)	100	Total W (%)	100

Requirements largely describe aspects of the problem to be solved and constraints on the solution (Egyed, 2001). Requirement analysis reflects sometimes conflicting interests of a given set of system's stakeholders.

Many authors list sources of stakeholder requirements. "Stevens et al. (1998)" provides a list of sources of users requirements and "Pugh (1991)", a set of additional sources of stakeholder requirements.

Requirements analysis is conducted iteratively with functional analysis to optimize performance requirements for the identified functions, and to verify that the elaborated solutions can satisfy stakeholder requirements.

The requirements refinement loop assures that a technical requirement maps the stakeholder values, assumptions and goals.

3.2. Definition of mission architecture elements and alternative options

The architecture elements definition, shown in "Tab. 2", models a solution to the problem described in the requirements that comes from the stakeholder analysis ("Tab. 1"). The terminology and concepts used to describe architectures differ from those used for the requirements (Egyed, 2001). Architecture deals with elements, which compose the system concept, capture and reflect the key desired value attributes (effectiveness) of the solution under elaboration.

In the context of requirements, architectural modelling has to satisfy the roles of supporting fast trade-off analyses about requirements' feasibility and stakeholder interests via architectural key elements options.

Table 2. Architecture elements and alternative options for a Generic Mission.

Mission Segment	**Architecture Elements**	**Alternative Options**
Segment 1	Element 1	Alternative 1
		Alternative 2
		Alternative 3
	Element 2	Alternative 1
		Alternative 2
Segment 2	Element 3	Alternative 1 ⋮
	Element 4	⋮
	Element 5	⋮
Segment 3	⋮	
⋮		

3.3. Decision drivers identification for each architecture element

This step, in the stakeholder value driven space mission architecture trade off, models the effectiveness attributes of alternative options such as cost, performance, schedule and risk. The model can be built through decision drivers which constitute the main mission parameters or characteristics that influence such attributes. These characteristics are the ones that the stakeholder or designer can trade off.

"Table 3" presents the effectiveness attribute model through identification of decision drivers built from Tab. 2. A set of cost decision driver should be responsible for model about 80% of the total alternative cost. Thus, a set of decision drivers which represents one system architecture should be responsible for model about 80% of the respective total solution cost. In this way, can be modelled all effectiveness attributes (cost, performance, schedule and risk) of a given architecture solution.

Examples of decision drivers that model the operation cost of a space system are: number of operators and infrastructure complexity.

Table 3. Decision drivers identification for a Generic Mission.

Architecture elements	Element alternatives	Cost decision drivers	Performance decision drivers	Risk decision drivers	Schedule decision drivers
Element 1	Alternative 1	Decision driver 1 (%C)	Decision driver 1 (%P)	Decision driver 1 (%R)	Decision driver 1 (%S)
		Decision driver 2 (%C)	Decision driver 2 (%P)	Decision driver 2 (%R)	Decision driver 2 (%S)
		Decision driver 3 (%C)		⋮	⋮
	Alternative 2	Decision driver 4 (%C)	Decision driver 3 (%P)		
		Decision driver 5 (%C)	Decision driver 4 (%P)		
	Alternative 3	Decision driver 6 (%C)	Decision driver 5 (%P)		
Element 2	Alternative 1	Decision driver 7 (%C)	Decision driver 6 (%P)		
	Alternative 2	Decision driver 8 (%C)	Decision driver 7 (%P)		
Element 3	Alternative 1	Decision driver 9 (%C)	Decision driver 8 (%P)		
		Decision driver 10 (%C)	Decision driver 9 (%P)		
⋮	⋮	⋮	⋮	⋮	⋮
		100 % ~ 80 % of total cost	100 % ~ 80 % of total perfor.	100 % ~ 80 % of total risk	100 % ~ 80 % of total schedule

3.4. Defining attribute value weight to stakeholders

"Table 4" shows how to transfer the stakeholder analysis (interests and importance from "Tab. 1") results to the attributes modeled through decision drivers (from "Tab. 3"). By this way, it is possible to translate the stakeholder value preferences towards cost, risk, schedule and performance attributes inside the space mission architecture trade off process. "Table 4" results are the attribute value weights to stakeholder. To have the AVW, each stakeholder value (interest) identified in stakeholder analysis should be associated with the corresponding decision driver(s). This association should take into account such as: the decision drivers system number of operators and infrastructure complexity should be associated with the stakeholder value cost of operation. The attribute value weight is the weighed mean of the multiplication between the importance that stakeholder gives for its interest and the weight that decision driver has for the attribute.

In this way, can be assessed the importance that stakeholder give to the each effectiveness attribute in the solution.

Table 4. Definition of the attribute value weight to stakeholders (AVW).

Decision drivers (cost)	Associated stakeholder values (cost)	W *C=AVC	AVW to stakeholder (%) AVC / Sum total AVC
Decision driver 5 (4% of C)	Interest 1 (5% of W)	20	%
Decision driver 6 (3% of C)	Interest 2 (10% of W)	30	%
⋮	⋮	⋮	⋮
		Sum total AVC	**Total 100%**

Decision drivers (performance)	Associated stakeholder values (performance)	W*P=AVP	AVW to stakeholder (%) AVP / Sum total AVP
Decision driver 1 (3% of P)	Interest 1 (5% of W)	15	%
Decision driver 2 (7% of P)	Interest 2 (8% of W)	42	%
⋮	⋮	⋮	⋮
		Sum total AVP	**Total 100%**

Table 4 (cont). Defining attribute value weight to stakeholders (AVW).

Decision drivers (schedule)	Associated stakeholder values (schedule)	W*S=AVS	AVW to stakeholder (%) AVS / Sum total AVS
Decision driver 5 (4% of S)	Interest 1 (6% of W)	24	%
Decision driver 6 (2% of S)	Interest 2 (10% of W)	20	%
⋮	⋮	⋮	⋮
		Sum total AVS	**Total 100%**

Decision drivers (risk)	Associated stakeholder values (risk)	W*R=AVR	AVW to stakeholder (%) AVR / Sum total AVR
Decision driver 5 (2% of R)	Interest 1 (3% of W)	6	%
Decision driver 6 (2% of C)	Interest 2 (5% of W)	10	%
⋮	⋮	⋮	⋮
		Sum total AVR	**Total 100%**

Up to here, it was introduced the stakeholder analysis within the architecture trade off process and modeled the stakeholder value attributes in the several architecture options. It has been used a well established pattern in the literature i. e., around 80% of the total life cycle cost, performance, schedule and risk attributes of a design are committed by decisions made during design concept exploration.

3.5. Stakeholder value trade off matrix (assessment)

The evaluation is done through the relationship matrix presented in "Fig. 4", which is built by using the information from "Tabs. 3 and 4". The matrix relationships are shown at the lines and columns crossing.

The last two columns are results obtained from the sum of products between attribute value weight (AVW) and element impact on architecture taking into account the decision driver relationship established in "Tab. 3". An evaluation of stakeholder satisfaction with architecture effectiveness is obtained trough sum of element results (one option for each architecture element).

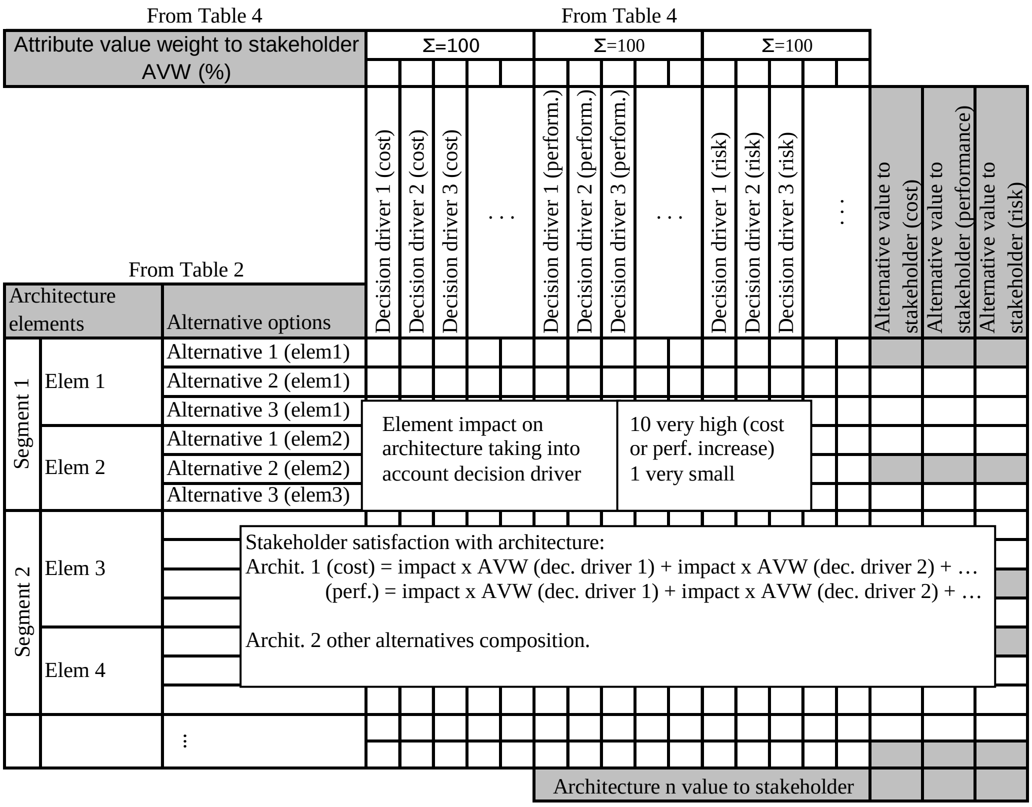

Figure 4. Stakeholder value trade off matrix

3.6. Selection rule definition and decision making

The expected result from the stakeholder value driven space mission architecture trade off process is to obtain a graph as shown in "Fig. 5" (theoretical mission case with performance, risk and cost as effectiveness parameters): the bent surface represents the envelope of the currently available technology in terms of stakeholder satisfaction with cost, risk and performance. The points (architectures) above the surface cannot be achieved with the current available technology i.e. they represent designs that are not feasible. The points (architectures) inside the envelope are feasible, but are dominated by designs whose combined cost, risk and performance lie on the envelope boundary. Designs represented by points on the envelope boundary are called stakeholder value effective (efficient or non-dominated) solutions.

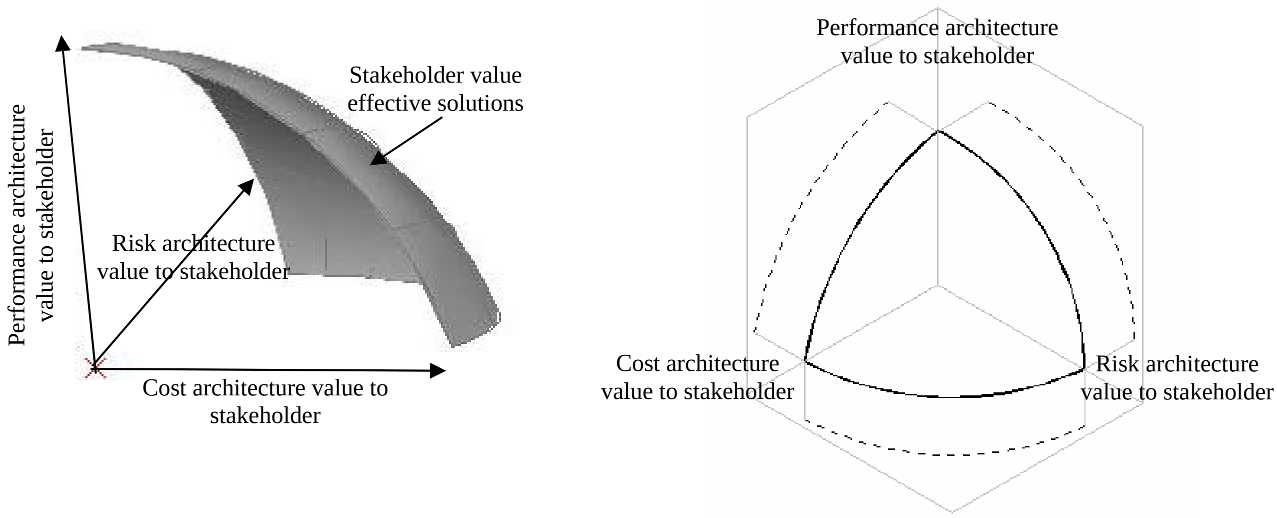

Figure 5. Theoretical pareto frontier obtained from stakeholder value trade off matrix (Figure 4)

The selection rule criteria for systems differ significantly. In some cases, to the stakeholders performance goals may be much more important than all others. Other projects may demand low costs, have an immutable schedule, or require minimization of some kinds of risks (Shinko, 1995). The WP, WR, WS and WC relative importance values defined in Section 3.1, "Tab. 1" should be used as reference to differentiate the stakeholder attributes. Then, the selection can be made taking into account the considerations as the explained above.

Considering cost, performance, risk and schedule drivers, a four dimension evaluation is obtained and a efficient region is found by the proposed process.

4. DISCUSSION OF STAKEHOLDER VALUE DRIVEN SPACE MISSION ARCHITECTURE TRADE OFF

In the late 1950s, the US government planned to take man to the moon. One of the fundamental tenets of the program management concept was that three critical factors-cost, schedule, and reliability-were interrelated and had to be managed as a group. This inicially held true for the Apollo program. The schedule, dictated by the president, was firm. Since humans were involved in the flights, and since the president had directed that the lunar landing be conducted safely, the program managers placed a heavy emphasis on reliability. Accordingly, Apollo used redundant systems extensively so that failures would be both predictable and minor in result. The significance of both of these factors forced the third factor, cost, much higher than might have been the case with a more leisurely lunar program such as had been conceptualized in the latter 1950s (Launius, 1994).

One of the critical early management decisions made by NASA was the method of going to the Moon. No controversy in Project Apollo more significantly caught up the tenor of competing constituencies in NASA than this one. There were three basic approaches that were advanced to accomplish the lunar mission: 1. Direct Ascent; 2. Earth-Orbit Rendezvous and 3. Lunar-Orbit Rendezvous.

Inside NASA, advocates of the various approaches contended over the method of flying to the Moon. It was critical that a decision not be delayed, because the mode of flight in part dictated the spacecraft developed. While NASA engineers could proceed with building a launch vehicle, the Saturn, and define the basic components of the spacecraft--a habitable crew compartment, a baggage car of some type, and a jettisonable service module containing propulsion and other expendable systems--they could not proceed much beyond rudimentary conceptions without a mode decision. The NASA Rendezvous Panel at Langley Research Center pressed hard for the lunar-orbit rendezvous as the most expeditious means of accomplishing the mission. Using sophisticated technical and economic arguments, over a period of months in 1961 and 1962 Houbolt's group advocated and persuaded the rest of NASA's leadership that lunar-orbit rendezvous was not the risky proposition that it had earlier seemed.

Today's space mission development requires a high level of sustainability that only can be given by stakeholders who provide financial, political, and economic support. Sustainability here refers to the fact that stakeholders will be assured to receive the required amount of value over a specified period of time. In this way, Moon's Exploration is much more driven by cost and performance than schedule and risk

Thus, the proposed method seems to be appropriate to the space missions architecture analyses.

5. CONCLUSIONS

Design methods present product development process in a systemized and organized way; however, the same do not occur with information and activities about the creation and evaluation of design alternatives. There are relatively few discussions about the trade off process in the literature (Larson, and Wertz, eds. 2003).

Defining and using performance, cost, risk and schedule parameters as decision drivers and transfering to them the relative importance of stakeholder interests (values) in a trade off process may promote a new paradigm: a evaluation (through relationship matrix) of the architectutre effectiveness through the value that the stakeholder gives to performance, cost, risk and schedule. In this way, the stakeholder satisfaction with the system effectiveness becomes more important in the management decisions.

Thus proposal presented in this paper provides a means for innovating the mission design process by interconnecting stakeholder needs, requirement analysis, concept exploration and decision drivers in order to capture in trade off process the value given by stakeholders to the architecture performance, cost, risk and schedule. The paper proposes a subtle but closer to reality paradigm shift: trade the importance stakeholders give to performance, cost, risk and schedule attributes rather then those attributes themselves

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