Assessing Alternatives in the Systems Engineering Process: Case Study of an Earth Observing Satellite Concept

Abstract

Defining design alternatives constitutes one of the critical initial steps of the systems engineering process [1]. Once these design alternatives have been identified, assessing which alternatives best satisfy the project's objectives can prove to be challenging when dealing with complex decision frameworks. Complex systems often involve the participation of different interest groups, who have different value systems and are focused on distinct aspects of the project. For example, design alternatives might be assessed predominantly for their technical merit by one group of stakeholders, while a different group might be more inclined to assess the design alternatives primarily based on programmatic values. MESCAL (Monitoring the Evolving State of Clouds and Aerosol Layers) is an ongoing NASA / CNES (Centre National d'Etudes Spatiales) joint study for an active remote sensing Earth observing satellite. Several design alternatives have been identified and the assessment of these alternatives requires consideration of a variety of factors.

This paper presents the approach that was used to support a global assessment of the MESCAL design alternatives. A mapping of the interactions between mission, instrument, and science requirements was modeled to support the assessment of the trade space. In addition, a set of metrics was developed to structure the assessment that was conducted. Finally, this paper also discusses the general applicability of these metrics to other science mission concepts in the formulation phase.

Keywords
Systems Analysis, Alternatives, Assessment

1. Introduction

The space mission analysis and design process is iterative in nature. Mission objectives, mission design alternatives, the evaluation of these alternatives, and the definition of the mission requirements are iteratively analyzed to develop an increasingly more refined mission concept [2]. A companion paper discusses the definition of design alternatives for a space mission concept in the formulation phase [3]. Here, we describe how these design alternatives can be assessed once they have been determined.

The assessment step of the mission analysis and design process is critical, as it enables narrowing the design space by prioritizing and selecting design alternatives. This step can also prove to be challenging. Many elements of the mission concept at the system, sub-system, and component levels offer design alternatives that need to be evaluated. These design alternatives cannot be assessed independently and serially. Different combinations of alternatives for the various elements can lead to drastically different integrated mission designs. An integrated approach to the assessment of design alternatives is key to understanding the interdependence of the various design options and their impact on the overall mission design.

In addition, complex systems involve the participation of varied groups of stakeholders, who have different interests and values systems. While some stakeholders may value the technical merit of a design alternative more than its programmatic merit, others might value low risk and low cost options more than meeting the set of initially defined mission requirements. It is the role of the space mission analyst to provide a holistic approach to the evaluation of the various design alternatives and to integrate the various value systems to enable team convergence towards a mission design.

The formulation of a concept for a novel Earth observing satellite is an example of such a complex system, which requires several iterative steps of the mission analysis and design process. MESCAL (Monitoring the Evolving State of Clouds and Aerosol Layers), a NASA / CNES (Centre National d'Etudes Spatiales) joint study, is used here as a case study. This paper describes how mission, instrument, and science interactions were modeled to capture the interdependence of the design alternatives. In addition, this paper discusses the approach that was adopted to integrate the value models of the various stakeholders. The international partnership introduces additional complexity to the assessment of design options, which renders common analytical decision making methods inapplicable. This paper presents the approach selected to assess the various design alternatives.

2. MESCAL

MESCAL is a NASA-CNES joint formulation study for a space borne High Spectral Resolution Lidar (HSRL) mission. MESCAL builds on the success of CALIPSO, a NASA-CNES backscatter lidar satellite, which has been providing "insights in the role that clouds and atmospheric aerosols play in regulating Earth's weather, climate and air quality" for over 11 years [4]. The MESCAL concept leverages advances made in HSRL technology from numerous airborne field studies led by a team of scientists and engineers at NASA Langley Research Center (LaRC) over the last two decades. MESCAL integrates these technology developments on a space platform to enable space-borne HSRL operations.

3. Mission, Instrument, and Science Interaction Modeling

Many design alternatives were identified at the component, sub-system, and system level. These alternatives cannot be evaluated independently, as many design decisions impact other elements of the system. For example, selecting a certain type of detector impacts the amount of required power, which then drives the selection of the bus platform. Conversely, selecting a specific high heritage platform would dictate the range of available power, which would then limit the number of detector options. Another example is the selection of the orbit altitude: a higher altitude requires a telescope of greater size to achieve comparable science measurements, which in turn impacts the required minimum fairing diameter on the launch vehicle.

Design alternatives are interdependent, and it is crucial to understand these dependencies in the assessment phase. In the MESCAL case study, the authors defined key elements of the system, for which design alternatives had to be assessed. Three categories of elements were identified: mission elements, instrument elements, and science elements. The software Cmap Tools (Florida Institute for Human & Machine Cognition) was selected to graphically represent these elements (nodes) and their interactions (connectors).

Figure 1 shows one of the models created for the MESCAL case study. The model provides a synthesized view of the interactions between the elements of the system. The visual representation identifies the number of connections for each node, highlighting which parameters are more interdependent than others and where the complexities of the system lay. Identifying these relationships early in the project life cycle allows for these relationships to be treated as trades during the mission formulation, rather than accepted as constraints. Designing and developing the system with this improved understanding can allow for greater satisfaction of the preferences of multiple stakeholders with differing value models.

4. Limitations of Traditional Decision Making Methods

Once alternatives have been identified, and once the role of each parameter is better understood in the system model, decision making methods are commonly applied to structure the decision process. The authors observed that the MESCAL case study faced limitations when considering traditional decision making methods, leading to the development of an alternative approach.

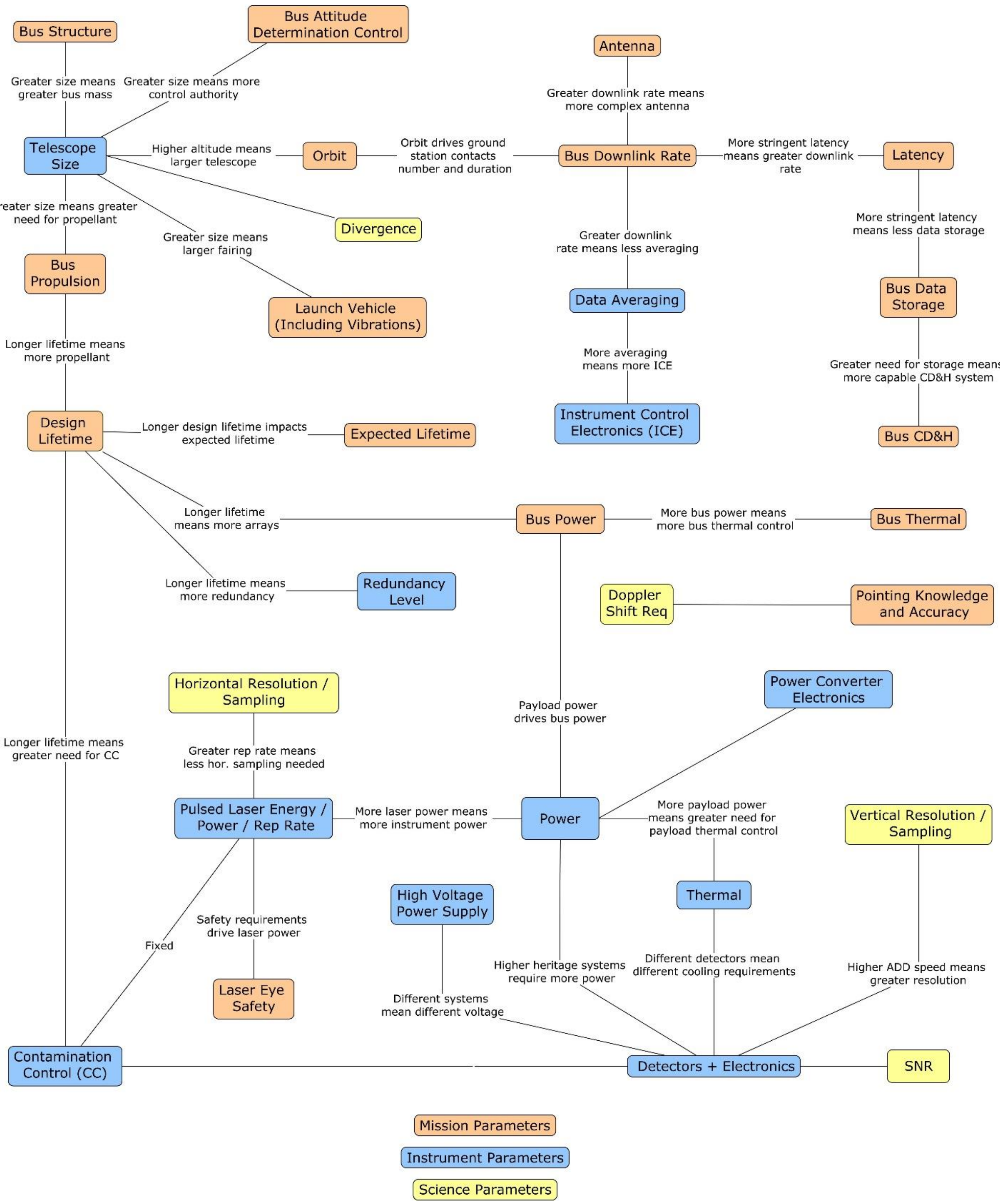

Figure 1. System-level modeling of mission, instrument, and science interactions

4.1 Traditional Decision Making Methods

Many methods have been developed and made available to decision makers to streamline and facilitate complex decision making activities. Decision makers can use Cost-Benefit Analysis to understand the relative value of a set of options, where the value of an option is the ratio of that option's benefits to its costs. This method is most applicable when the decision problem can be treated as an optimization problem of a single variable (the value), but has limitations when multiple objectives and/or qualitative metrics are included, as described by Cascetta et al. (2015) [5]. Multi-criteria decision analysis (MCDA) emerged as a discipline to facilitate making decisions in scenarios with these additional complexities. In the 1960's, Bernard Roy developed a ranking and veto system, the ELimination Et Choix Traduisant la REalite (ELECTRE) method (Elimination and Choice Expressing Reality) [6]. In the following years, Thomas Saaty created the Analytical Hierarchy Process (AHP) to derive priority vectors from matrices of pairwise comparisons. Other methods include Bellman and Zadeh's fuzzy sets, first developed in the 1970s, which transform qualitative linguistic statements into mathematical expressions [7], and Hwang and Yoon's Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), developed in 1981 [8].

4.2 Inapplicability in MESCAL Case Study

After the initial phase of definition of the alternatives, the authors considered several decision making approaches to perform their assessment. However, the unique complexity of the case study made it challenging to use these methods in their traditional form. Due to the international nature of the project, significant inherent discrepancies exist between value models, which rendered methods such as AHP inapplicable. AHP sequentially uses "decomposition**,** comparative judgment and synthesis of priorities" [9]. An initial attempt at applying an AHP framework showed that while the problem decomposition was achievable, the ranking of alternatives by comparative judgment would not be feasible. For example, one of the figures of merit against which alternatives were evaluated assessed the alignment of a given alternative with the institutional benefits gained by the agencies, such as workforce and facilities utilization. The ranking of such a figure of merit is challenging in the case of an international partnership, where each partner is interested in capturing work. Selected alternatives would thus be scored highly by one partner and lowly by the other, where no convergence was possible and any score combination was meaningless. The flaw did not reside with the definition of the metric itself, as it is a critical criterion which cannot be ignored in the evaluation process. Rather, the nature of the system makes it infeasible to quantify each stakeholder's value models with traditional decision making methods.

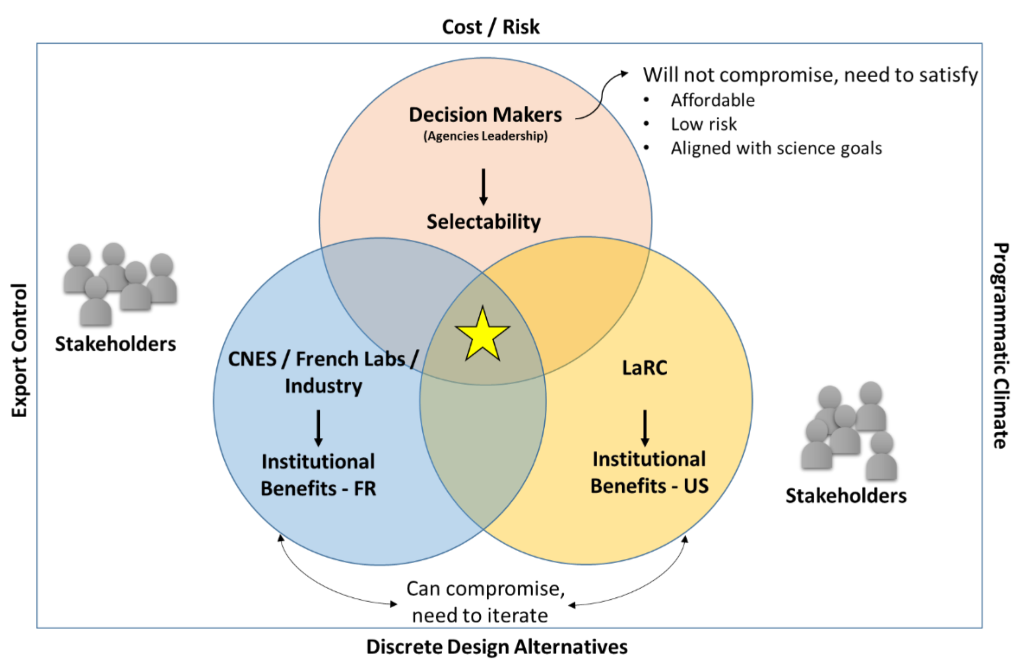

Figure 2. MESCAL Decision Framework

Figure 2 graphically illustrates the complex nature of the MESCAL decision framework. The optimal alternatives need to satisfy value models of three main groups. The first group consists of the French partners in the study, composed of CNES, the French research labs who lead the science component of the effort, and the French industry. A second set is held by NASA Langley Research Center, where science, engineering and mission design are co-located. The final set is held by the decision makers, which reside within both agencies' leadership teams. The decision framework is bound by four sets of constraints, as represented in the figure. It should be noted that while the figure emphasizes the three main groups involved, there are several sub-groups within each primary group that may also hold varying value models. The figure highlights the complexity of the decision framework, which is well outside of the typical decision environment where traditional methods are applicable. While an analytical solution could be designed to reconcile large discrepancies between value models, a non-analytical approach was selected for this study to rapidly achieve useful results for the study.

5. Alternative Approach to Perform the Assessment of Alternatives

Due to the complexity of the decision framework and the number of partners involved, it was not practical to reconcile and prioritize all value models. Since a quantitative approach was not feasible, the authors elected to use a qualitative approach instead. The initial step of problem modeling and decomposition in AHP was retained. A set a figures of merit was defined with the intent to structure the conversation and provide a common set of metrics used by all to assess the design alternatives. The metrics were defined according to common practices when framing decision problems: their number is limited to enable a global cognitive perception of the metrics as a set, they are independent and orthogonal, and they are cross-cutting. The set was then used to systematically evaluate design options, enabling a comprehensive assessment of the alternatives.

5.1 Selected Metrics for MESCAL

The metrics were defined as follows:

- **Mission selectability:** The potential total impact on the selectability of the mission concept. Includes the perception of the partners' capabilities, the perception of risk, and the level of heritage of the design alternative.
- **Achieved science:** The level to which the achieved science advances the current state of the art and aligns with science advisory boards.
- **Alignment with institutional needs:** The level to which the alternative aligns with CNES and LaRC's strategic objectives and mission statements. Also encompasses the institutional need to sustain the workforce and utilize facilities.
- **Mission risk:** The level to which the given alternative generates risk in the development and production phases of the mission. Includes the number of organizations that are involved, the risk of schedule and cost overruns, the integration complexity at the interface level, and the experience of the partners for selected sub-systems and roles. Encompasses both technical and programmatic risk.
- **Mission sustainability:** The potential impact on the sustainability of the mission concept after selection and initial funding. Includes the susceptibility of the mission to cancellation and the likelihood of the mission being sustained throughout evolving programmatic climates.

5.2. General Applicability

These metrics have been used to structure comparisons of concepts within MESCAL; however, they also have applicability to other missions. Selectability is relevant to any mission that is competitively proposed, although the specific contributors to selectability will depend upon the nature of the proposal and the decision makers that evaluate it. Achieved science encompasses the metric most familiar to many principal investigators, project scientists, and other key contributors to the development of a mission concept. Alignment with institutional needs may not always be directly relevant to a project, but the larger institution that staffs and facilitates that project may place high value on it. Mission risk is often a critical factor in the evaluation of feasibility of proposed concepts. Mission sustainability, as with the alignment metric, is a metric that may be more relevant to an institution than a specific project, but is nonetheless tightly coupled between the internal and external aspects of a mission. While used here for a specific Earth science mission, these metrics are applicable to a broader class of concepts across other domains of science.

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