Value Network Modeling

A Quantitative Method For Comparing Benefit Across Exploration Architectures

by

Bruce G. Cameron

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ABSTRACT

In the design of complex systems serving a broad group of stakeholders, it can be difficult to prioritize objectives for the architecture. I postulate that it is possible to make architectural decisions based on consideration of stakeholder value delivery, in order to help prioritize objectives. I introduce the concept of value network models to map out the indirect benefit delivered to stakeholders. A numerical methodology for prioritizing paths through this network model is presented, with a view to discovering the most important organizational outputs.

I show how value network models can be linked to architecture models to provide decision support to the architect. I present a case study to examine the connectivity and sensitivity of a test architecture to value delivery. I conclude that a limited subset of NASA's outputs will discriminate between architectures. In this manner, I show how value considerations can be used to structure the design space before critical technical decisions are made to narrow it.

A number of organizational implications for value delivery are generated from this analysis. In particular, I show that benefit flows should be aligned to organizational processes and responsibilities, and that failure to map stakeholder input to architecture evaluation can weaken benefit.

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1. Introduction

A critical aspect of future space exploration is sustainability. Technical success alone cannot ensure that space exploration will have the continuing societal support necessary over the course of decades to develop enduring and expanding exploration capabilities. I define sustainability using a four-fold approach: valued benefits to all stakeholders, affordability, risk management that communicates residual operational risks to stakeholders, policy robustness to improve the chances of success in a changing political environment[1,2,3]. In this thesis, I focus on modeling the first pillar of sustainability, how value is delivered to a wide range of stakeholders. The exploration enterprise includes the core set of explorers, scientists, and engineers that realize and execute the space exploration campaign. It also includes the extended group of stakeholders who are not directly involved in the exploration campaign, but who are nevertheless crucial in providing support and funding. I assert that all stakeholders must be aware of the benefit derived from the exploration value delivery system and of its delivery mechanism in order for the organization to be sustainable.

Current requirements analysis tends to select architectures based on technical merit, and then build in consideration of stakeholders much later in the design process. Requirements analysis is well developed as a method for translating opportunities or needs into system requirements[4,5]. In many cases, the identification of requirements is levied from the customer-specified technical requirements or past technical systems, without examining where needs derive from. Furthermore, there is often a selection bias which tends to highlight technical needs because they can be more easily quantified as requirements. I assert that requirements analysis has not mated well with stakeholder analysis in the past, because of difficulties translating between the output of stakeholder analysis and the inputs for requirements analysis.

Prof. James Wilson notes that this problem is not unique to requirements engineering, and is in fact exacerbated for government programs where no competition exists:

> "The tasks of operators in private organizations with vague goals become defined through a process of trial and error and internal negotiation that is then tested by competitive natural selection. The tasks of operators in government agencies with vague goals are probably set in much the same way, but without a regular test of the fitness of the solution. […] When the agencies have vague or inconsistent goals (as is usually the case), what the workers do will be shaped by the circumstances they encounter at the job, the beliefs and experiences they bring to the job, or the external pressures on the job."[6]

I propose that a sustainable exploration value delivery system results from deliberate design decisions, and that those design decisions are best realized through an understanding of the system's stakeholders, their values and needs early on in the process. Once values and needs are identified, system requirements can be defined, leading to the development of specific architecture choices not only for the exploration technical system, but also for the exploration enterprise and operating concept, as well as its policy environment.

The general objective of this thesis is therefore to analyze this gap between benefit and requirements, and, more importantly, to provide a process for bridging the gap between stakeholders' considerations and requirements analysis for large, complex systems.

The use of stakeholder analysis has grown steadily, diffusing in from rising interest in corporate governance[7]. This reflects a growing sense that the organization should act on the interests *and* values of its stakeholders. While interest on the corporate front centers around whether or not 'maximizing stakeholder value' is an appropriate measure of success, public enterprises are forced to tackle the key issues head-on, given that profit is not an available metric.

The key question for public enterprises is therefore how to measure value? I define value as a benefit perceived by the receiving party at the cost required to obtain it, which is a simplification of the Lean Enterprise definition of value : "how various stakeholders find particular worth, utility, benefit, or reward in exchange for their respective contributions to the enterprise"[8]. Benefit is always recorded from the perspective of the recipient, in an effort to capture the change in the stakeholder's attribute that is actually related to value. Value is created by the organization in question by using its resources to create an architecture which produces outputs that satisfy the needs of its stakeholders. In this manner, I abstract across a number of different transactions (e.g. goods, services, information, political influence) and disciplines (e.g. systems engineering, science, political science, economics) using the language of value. Identifying which entities are stakeholders shapes the network boundaries, scope, and the types of value that are considered in the analysis. It is therefore important that the choices of stakeholders are consistent with the intended scope of the value flows.

Questions of value and stakeholder analysis are increasingly present in systems engineering analysis. For example, NASA Systems Engineering Handbook of 1995 [Hoffman] makes no reference to stakeholders, but a recent NASA study, the Exploration Systems Architecture Study[9], references consulting and communicating with stakeholders tangentially. The most recent version of the NASA Systems Engineering Processes and Requirements document (published March 6 2006) now requires stakeholder analysis as the first step in the requirements definition process, in order to "elicit and define use cases, scenarios, operational concepts, and stakeholder expectations"[10].

The specific objective of this thesis is to showcase a modeling technique by which stakeholder analysis can be used to differentiate between architectures. Large public architectures represent the ideal case study, because they do not have easily-derived technical requirements, and the proliferation of non-technical needs forces us to examine the bias in requirements-setting.

Specific Objective
Demonstrate a modeling technique by which stakeholder analysis can be used to differentiate between architectures.

Much of the discipline of system architecture has focused on methods for abstracting information from downstream in the design process up into the initial decision period. Techniques like parametric subsystem models and functional decomposition have facilitated this process. This thesis aims to do the same for the feedback systems from stakeholders that occur later in the design process.

While this thesis is written using NASA's exploration value delivery system as the primary example, an effort is made to highlight the generic process, given that this process is broadly applicable.

This thesis is organized into four main chapters. The first explores the background and context for system architecture and stakeholder analysis in the literature and the available course material. The second chapter develops a network model for understanding the stakeholder context, and presents a quantitative methodology for sorting amongst different benefits. The third chapter showcases the results from this model. The fourth chapter presents a methodology and a test case for linking this network model directly to an architecture.

2. Background

In this section, the relevant literature on related topics is presented, as well as the previous work performed at MIT on value modeling. The literature search is subdivided into three sections:

Stakeholders and Complex Systems: This section delves into the academic context and motivation for the research.

Network Theory: Overview of the computational techniques available for network modeling.

Organizational Design: The relevant background on designing an organization for value delivery.

The literature search is then followed by a discussion of the previous work completed in this area of research.

2.1. Literature Search

2.1.1. Stakeholders and Complex Systems

Who are Stakeholders?

Modern stakeholder theory originated with Freeman's *Strategic Management, A Stakeholder Approach*[11], published in 1984. The main tenets of stakeholder theory, as summarized later by Sternberg[12] are:

1. Organizations are accountable to all their stakeholders
2. The objective of management is to balance stakeholders' competing interests

While a number of different management strategies are given in Freeman, ranging from defining stakeholders as only those who hold stocks in the organization to a Rawlsian strategy aimed at creating social change, the approach pursued in this thesis follows most closely in the Utilitarian tradition, which aims to maximize benefit across a diverse base of stakeholders.

Donaldson and Preston[13] provide an overview of the discipline's justification. They note that stakeholder theory is difficult to falsify, in that differing degrees of 'stakeholder management' are difficult to quantify, and that no true empirically tested hypotheses are presented in the literature. Many arguments based on the descriptive power of stakeholder theory are given, and an attempt is made to formally link the discipline to agency theory, microeconomics, and contract theory.

One of the key questions in stakeholder theory is who to consider a stakeholder. One could attempt to capture all those who can have an impact on the organization, or more broadly, all those who are impacted by the organization.

According to Kochan and Rubenstein[14] there are three key criteria for categorizing stakeholders:

1. Stakeholders must hold assets that are critical to the enterprise's success
2. Stakeholders must put their assets at risk in the enterprise
3. Stakeholders must have sufficient power to compel influence.

Sternberg offers a strong caution of adopting too broad a definition, noting that stakeholder theory doesn't explicitly enable a prioritization of stakeholders. She also notes that even restricting stakeholders to those parties that affect the organization is too broad, noting that burglars should not be considered stakeholders. Finally, Sternberg notes that stakeholder theory doesn't provide guidance on mechanisms for resolving conflicts between stakeholders.

I use a narrow definition of the term stakeholder, requiring the possibility to affect the organization, as well as receiving some sort of output from the organization (i.e. having a stake). Based on this definition, one can then a separate group called beneficiaries, who receive outputs but do not have the ability to influence the organization.

What is a Complex System, Why Might It Involve Stakeholders?

The term complex system has been defined by Crawley as:

Crawley's Complex System: Having many interrelated, interconnected, or interwoven elements and interfaces[15].

Embedded in this idea are two assumptions:

1. The complexity is not easily represented. For example, an integrated circuit with several AND/OR logic gates has many interconnected elements, but can be easily represented as a circuit diagram with several instantiations of AND/OR gates
2. The overall behavior of the system depends on many of the constitutive parts (if it was dependent on only one, the behavior would be easy to describe).

Two additional definitions of complex systems are:

De Weck and Magee's Complex System: A system with numerous components and interconnections, interactions or interdependencies that are difficult to describe, understand, predict, manage, design, and/or change.[16]

Sussman's Complex System: […] composed of a group of interrelated units (component and subsystems), for which the degree and nature of the relationships is imperfectly known, with varying directionality, magnitude and time-scales of interactions. Its overall emergent behavior is difficult to predict, even when subsystem behavior is readily predictable.[17]

Note that de Weck's and Sussman's definitions layer on the idea of uncertainty or imperfect information, not included in Crawley. Given that complex systems are not well understood, it is natural to layer additional observed behaviors, although it is not necessarily known whether these behaviors *cause* the complexity or not.

Mostashari[18] provides a good system for classifying types of complexity:

Behavioral complexity occurs when the emergent behavior of the system does not seem to relate to the individual behavior of the subsystems.

Structural complexity "is a measure of the interconnectedness of the structure of the complex system" [Mostashari, p.40].

Evaluative complexity denotes the idea that different actors can have different perceptions of the system, particularly differences in the valuation of outcomes.

Nested complexity occurs when each subsystem can be a complex system in its own right. Therefore, it is not necessarily feasible to increase the overall detail of a model in order to get to a level that has no uncertainty.

This is but a brief sketch of some of the factors that are often associated with complex systems. As with all models, complex systems models aim to capture the behavior of interest using a particular subset of the information available. Stakeholders are one of these possible information sources which can increase the complexity of certain systems.

First and foremost, multiple stakeholders can increase the evaluative complexity of the system, given that each does not necessarily derive the same benefit from the system. Second, stakeholders can increase the structural complexity of the system, as they provide resources that connect into the complex system, and they receive some portion of the output of the complex system (i.e. there are interfaces between stakeholders and the system which require structure in the system).

One can then ask what types of complex systems would we expect the stakeholder-related complexity to play a central role in the overall complexity of the system, and by therefore, our understanding of the system? For example, we would expect large public engineering projects to have numerous, conflicting stakeholders, like the FAA's Air Traffic Control System. However, for a complex system under private ownership, with sufficient central authority, one might not expect stakeholder considerations to dominate, like the Pickering, Ontario nuclear power plant. We might reasonably expect the importance of stakeholder consideration to scale with the number of stakeholders, the relative power of stakeholders, and the extent to which stakeholders have strong preferences about the design of the system.

One can imagine that the motivation for considering stakeholders might come in two forms:

1. Pull: There is an immediate need to manage the stakeholders, because they will obstruct the process if not satisfied
2. Push: The organization has managed to deploy the complex system, but for the next iteration, it perceives that stakeholder consideration could garner it more benefit. This would be more likely in a market environment.

The remainder of the thesis presumes that appropriate motivation for considering stakeholders has been identified, and the question remains how to manage them. The next section starts this thread by identifying what avenues exist for integrating stakeholders needs into a design.

Approaches to Integrating Stakeholders In Complex Systems

There are three possible ways to include stakeholders in complex systems planning, in order of increasing stakeholder involvement:

1. Analyze stakeholder dynamics to create a prioritization of stakeholders, for use as a rough heuristic
2. Capture soft priorities & determine metrics by which stakeholders want design to be evaluated
3. Map stakeholder needs directly onto the design

These are discussed in order below.

1. *Analyze stakeholder dynamics to create a prioritization of stakeholders, for use as a rough heuristic*

This was touched on above in the literature for stakeholder theory, in terms of the descriptive effort by stakeholder theorists. However, no mode of quantitative analysis was discovered in the literature purely on stakeholder dynamics, which partially defines the niche for this thesis. More specific elements of the literature that focus on elements of stakeholder dynamics relative to my quantitative framework are covered in the development of the quantitative framework.

2. *Capture soft priorities & determine metrics by which stakeholders want design to be evaluated*

This topic is the subject of many ESD monographs. Soft priorities include flexibility, manufacturability, sustainability, and risk minimization. While there is no limit to the number and type of soft priorities stakeholders might care about, all metrics share common characteristics, as explored below.

Harry Cook[19], a Professor in Product Development at the University of Chicago at Urbana-Champaign focusing on the Auto Industry, provides an excellent overview of possible methods for determining and evaluating metrics, from a product development perspective. He focuses on customers as the primary stakeholders, citing the economic theory behind pricing goods (price being the top metric for commercial products). Utility theory is discussed (mapping 'usefulness' as a function of performance), as well as prospect theory (utility theory when the benefits can be uncertain) and willingness to pay (defining value as the maximum exchange rate of goods & services for money). A closely related concept to WTP, Willingess to Accept (WTA), which seeks to define the bottom end of the scale, is relevant but not discussed in Cook.

Interestingly, Cook decouples benefit from cost in most of his research. Theoretically, benefit (or performance) and price are two separate metrics by which customers evaluate a product. The MIT approach has been to couple these in the concept of value, which is defined as benefit at cost (crudely, benefit less price where if both can be expressed in the same units). However, Cook first examines the problem of benefit, which he encapsulates as 'quality', and then examines the price that can be extracted for a defined benefit. He later sketches curves of Value-Cost [Cook, p. 188], the equivalent of the MIT value concept, but does not explore the benefit-price space broadly.

Cook references a framework for quality, which defines eight dimensions according to Garvin[20]:

- Performance – Attributes central to the function of the product
- Features – Attributes not central to the function of the product (ex. radio in a car)
- Reliability
- Conformance – Actual performance meets stated performance
- Durability
- Serviceability
- Aesthetics
- Perceived Quality – Essentially customer satisfaction

Cook then provides a number of interesting studies of benefit as a function of performance for cars. For example, he graphs benefit as a function of front leg room, using an exponential model relative to an inputted 'baseline' leg room, which is defined as having benefit of 1.

On the whole, Cook's approach favors several smaller metrics for benefit. The majority of his work is developing these metrics, rather than identifying metrics, because the dimensions of benefit for his product are well defined by past designs.

3. *Map stakeholder needs directly onto the design*

The third method for integrating stakeholders into complex system design, 'Map stakeholder needs into the design', has been the subject of significant research in product development, and manufacturing, among others. I call the key challenge here *The Problem of Requirements Derivation:* Given that you know who your stakeholders are, how do you capture what their needs are, and how do you map them onto the design? A survey of some methods for requirements derivation are presented below.

Kano's method[21], developed by Prof. Noriaki Kano of Tokyo Rika University, provides a framework for assessing the importance of product qualities from the customer's perspective. According to Kano, all product attributes can be grouped into one of three main categories, Must Be, One Dimensional, or Exciter, according to the level of customer satisfaction obtained for a given functionality of that attribute. For example, brakes on a car are a Must Be attribute, in the sense that the customer is dissatisfied if they are not present, but is not particularly satisfied if they are present – brakes are an expectation. Gas mileage on that car would be a One-Dimensional attribute, in the sense that the more functional the gas-mileage attribute, the more satisfied the customer is. Video screens in a car would be an Exciter attribute, in that most customers are not disappointed if they are not present, but they are excited if they are present. two additional are also possible, Indifference (where satisfaction doesn't change with increasing functionality) and Reverse (where functionality increases dissatisfaction).

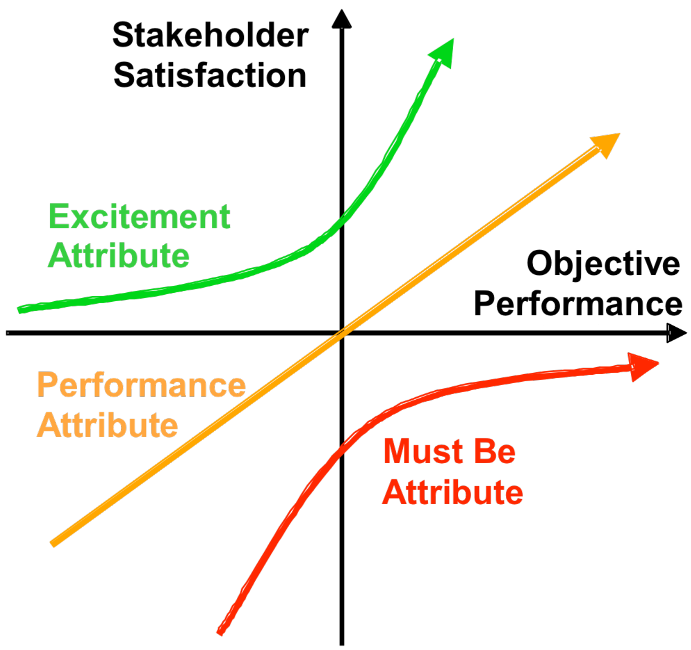


Figure 1 Kano Categories

The Kano method describes how two questions (one functional, one dysfunctional) per attribute can be used to determine which category each attribute falls into. While these questions are easily drafted for products, particularly where the architecture has already been determined, it is not always reasonable to ask the dysfunctional question, particularly in a policy setting. For example, one could not reasonably ask "What if NASA does not receive funding from Congress?". Therefore, in some cases, the questions must be modified for environments where relative change dominates. Another possible shortcoming of the Kano method is that it uses mostly existing forms to describe the theory, thus focusing his theory more on the requirements and design-facing considerations rather than needs.

Kano's theory compares favorably with other similar studies, which also highlight three main types of needs. For example, in a marketing study "The results, based on a sample of employees in marketing communications and public relations agencies, show that three different levels of exchange and communication – inevitable, necessary and desirous levels – can be expected"[22].

Kano's theory was motivated by a broader study of quality control measures in Japanese firms.[23] His criteria were used as the first step to defining what type of quality customers wanted, which was followed by a number of methods to attempt to design and manufacture to that quality. A number of quality methods have arisen since, some of which merit mention here for their methods of understanding quality.

Quality Function Deployment (also called Quality Deployment and the Taguchi method) arose out of the manufacturing sector in Japan. QFD aims to translate Customer Requirements (CRs) into Technical Attributes (TAs), keeping careful watch of the competition.

There are several key ideas in QFD[24]:

1. Use a matrix to map CRs to TAs, with different strengths of relationships
2. Record which TAs are coupled (a rough design model)
3. Use a prioritization of the TAs as an input to the design (derived from prioritization of CRs)
4. Establish numerical target for TAs
5. Benchmark satisfaction of CRs against competitors

In particular, QFD methods aim to capture the above information in a single diagram, to facilitate inter-disciplinary dialogue about the problem.

Chen et al. [25] note there is uncertainty associated with translating Customer Requirements into Technical Attributes because there is are multiple mappings of CRs into TAs as each customer requirement could be satisfied by multiple TAs. Some interesting work has been done on using fuzzy numbers to express the relative priority of CRs, as well as the mapping of CRs to TAs, in order to better capture the associated uncertainty.

Lean, as derived from the Toyota Production System, focuses on identifying processes that impact value to the customer. Its focus on process, rather than creativity, architecture or design, belies its origins in manufacturing. However, Lean has been expanded to administration and product development, with mixed success. A recent MIT thesis by MacKenzie describes how value stream mapping can identify processes of interest to stakeholders. He notes that, with good data on the relative durations of different processes, time can be used a metric for cost, therefore a determination of value can be performed. Specifically, a tool to map the time required for different processes was used. However, in the absence of good timing data, or where activities don't contribute linearly to value, it can be difficult to link this analysis back to stakeholders. Additionally, MacKenzie's analysis requires an existing process, and is therefore less useful for new designs. MacKenzie proposes a rudimentary segmentation of stakeholders, by which processes for low value stakeholders would be outright eliminated as 'wasteful'. In this respect, Lean doesn't provide a framework for mapping stakeholder needs onto the design – rather, it provides a possible mechanism for evaluating the implementation of a design relative to stakeholders.

If all we were interested in was ranking stakeholder needs, we might also consider *Conjoint Analysis* or *Analytical Hierarchy Process*[26]. Given a set of stakeholder needs, these methods generate a ranked list by performing pair-wise comparison of all needs for a given stakeholder. We would still need a method to determine how many needs to satisfy for each stakeholder, and we haven't learned anything about the stakeholder's relative priority of these needs to needs not serviced by our actions. Additionally, the pairwise comparison process can become tedious for more than 5 or 6 needs.

As seen, a number of methods have been developed for capturing stakeholder and customer input for the design of complex systems. The choice of method and the level of detail of the analysis depends largely on what the desired output of the stakeholder analysis is, and how stakeholder input compares with the other upstream influences on the architecture (competition, regulations, human resources, capital, etc.). Before delving more deeply into the specific stakeholder considerations that might be interesting to represent, it would be worthwhile to investigate some of the other dimensions of complex systems that have been represented previously.

2.1.2. Modeling Complex Systems

A number of different types of models are used for modeling complex systems, depending on the application. Because I define complex systems as capturing several different types of information, these models necessarily bridge several disciplines. Some examples include:

Multidisciplinary Physical Models: Bringing together several disciplinary models, the complexity in these models arise from coupling between subsystems. An excellent example is the WingMOD MDO model created by Willcox to model the structural and aerodynamic aspects of a Blended Wing Body aircraft[27].

Network Models: These models address systems where the complexity arises from the quantity of actors / subsystems, rather than from significant coupling between any two actors / subsystems. Modeling of air transportation networks or supply chains fall in this category, such as the SpaceNet space logistics model[28].

Systems Dynamics: This discipline models systems which have time delays or a feedback structure. System dynamics models capture complexity in the form of non-traditional or abstract couplings between actors / subsystems. A number of other model types exist which capture the time dimension, notably the Critical Path Method (CPM)[29] for project management. In CPM, a series of processes are assigned completion times and interdependencies, from which the longest route through the network can be calculated, representing the minimum time necessary to complete the project. Some more recent CPM models have also included use of shared resources.

Recognizing the old saying "All models are wrong", each of the above types of model captures a particular dimension of a complex system. What we represent boils down to what we would like to capture about the system. The choice of dimensions should reflect the decisions to be made, the availability of appropriate data, and the organizational context into which the results will be integrated. With a view to examining the operational realities a value model will face, the next section provides an overview of the literature at the intersection of organizational design and system architecture.

2.1.3. Organizational Design

This section attempts to address the literature coverage of organizational realities. While the two previous sections began to walk through theoretical methods that lead to better design for value, this section will attempt to provide some context for value decisions, highlighting some of the litmus tests that can be applied to check a method for initial feasibility.

There are two dimensions of organizational behavior that would be worth considering here, which is explored in more depth below:

1. How do stakeholders typically interact with an organization?
2. How are decisions actually made?

How do stakeholder typically interact with an organization?

Resource dependence theory maintains that an organization's stakeholder interaction varies as a function of the resources it requires from stakeholders. Coff[30] focuses on bargaining power (some of which is grounded in resources) as the determinant of stakeholder outcomes. Coff highlights 4 dimensions of bargaining power: the ability to act together, access to information, replacement costs to the firm if a stakeholder exits, and cost of exiting to the stakeholder. Although in government scenarios, stakeholder exit might not be a realistic policy, Coff's position could be extended to include costs of reduced stakeholder involvement.

Craig attributes the success of the NASA robotic exploration programme to the existence of a "coherent external agent, The National Academy of Sciences"[31]. The existence of a clear and responsive client creates clear lines of communication, and a sense of oversight on value. Craig suggests that giving an external agency (whether it is a currently stakeholder or not) an oversight role would change the dynamics of stakeholder interaction, essentially by creating approval resources that NASA would need.

Assuming that an organization has an interest in engaging its stakeholders, one then has to ask the question of whether these stakeholders have an interest in interacting with the organization. Certainly this will depend on the history of interactions between the two, particularly whether the organization was seen to be responsive to external concerns. However, in addition to historical relationships, stakeholders may have reasons to guard information. Pfeffer[32] notes that stakeholders with high bargaining power may only interact with the organization when it is necessary to release information in order to make their outcome the obvious choice.

How are decisions actually made?

A preliminary reading of political economy reveals a key axiom: All bureaucracies act to preserve their own existence. Allison opines that "a government consists of a conglomerate of semi-feudal loosely allied organizations, each with a substantial life of its own"[33]. He continues, stating that Standard Operating Procedures are a natural result of the breadth of the mission of governmental agencies and the coordination required to deal with a complex set of constraints. Changes in these SOPs are more likely to occur after dramatic budget swings or performance failures.

These comments echo Wilson's quote on the effect of organizational culture on decision-making. Wilson quotes Roger Boisjoly, a whistle-blower at Morton-Thiokol in the Challenger accident, who states "nobody [raises objections] without a complete, fully documented, verifiable set of data" [Wilson, 104]. Wilson also notes that in a constraint-heavy public organization, "managers have a strong incentive to worry more about constraints than tasks, which means to worry more about processes than outcomes" [Wilson, p 131]. While this paints an negative picture of change in large organizations, it also emphasizes that any inclusion of a model as part of a process must have strong ties to outcomes to overcome the focus on tasks.

Switching focus to the external component of the decision-making process, a number of works have explored the idea that decision makers can be understood as bargaining agents attempting to form coalitions. Weible discusses the advocacy coalition framework for explaining the behavior of policy actors. He states that ACF "predicts two precursors to a major policy change: changes in beliefs of a dominant coalition or changes in available resources and venues [sic] which are brought about external shocks, policy-oriented learning, or hurting stalemate"[34]. In the context of my model, external shocks (like a political shift in the Congress) would be considered exogenous, policy-oriented learning would be captured, but is not considered a driver of change, and hurting stalemate would only be captured if regret were incorporate (as stalemates rarely arise out of benefit).

The difficulty in organization theory is that differences across organizations and decisions make it difficult to create general principles, beyond the basics of incentives, power, and coalitions. Therefore, many of these issues are treated in the NASA context through the thesis, recognizing however that there is a limit to how specific one can make the context without delving into individual organization trees.

Having now examined some of the relevant background for the benefit, stakeholder, modeling, and organizational context in which the central architecting questions of this thesis lie, I proceed to discuss some of the previous work on stakeholders conducted at MIT.

2.2. Previous MIT Work

This section attempts to provide a brief overview of the intellectual work and the context for this work previous to my arrival in September 2005.

There are 5 main contributors, whose work I will artificially segregate to simplify the discussion. The majority of this work was performed during the NASA Concept Exploration and Refinement study over the 2004-2005 academic year. As such, the complex system under study was originally the NASA lunar transportation system.

The overall framework for the system architecture work was created by Ben Koo[35], in collaboration with Bill Simmons and Ed Crawley. The premise is that aerospace applications often do a poor job of examining the entire design space. Rather, a number of possible approaches are identified, then one or two are chosen for detailed study based on a past experience, judgment, and legacy considerations. Koo's innovation was to create a modeling framework to force the designer to enumerate all of the variable choices for the architecture, and then formally express the constraints between different variable choices in the concept of the design, yielding a much broader architecture space than is typically considered. A screenshot of Koo's modeling language is shown in the figure below, for a specific model built by Simmons. Once all feasible architectures are enumerated, they are ranked using metrics, in order to select a subset for detailed study. It is worth noting that solid parametric models are a requirement for this approach, in order to determine the attributes of given architecture for input to the metrics based only on the selection of its architecture variables. The placement of metrics on the critical path to architecture selection is suggestive of possible stakeholder-related benefit metrics.

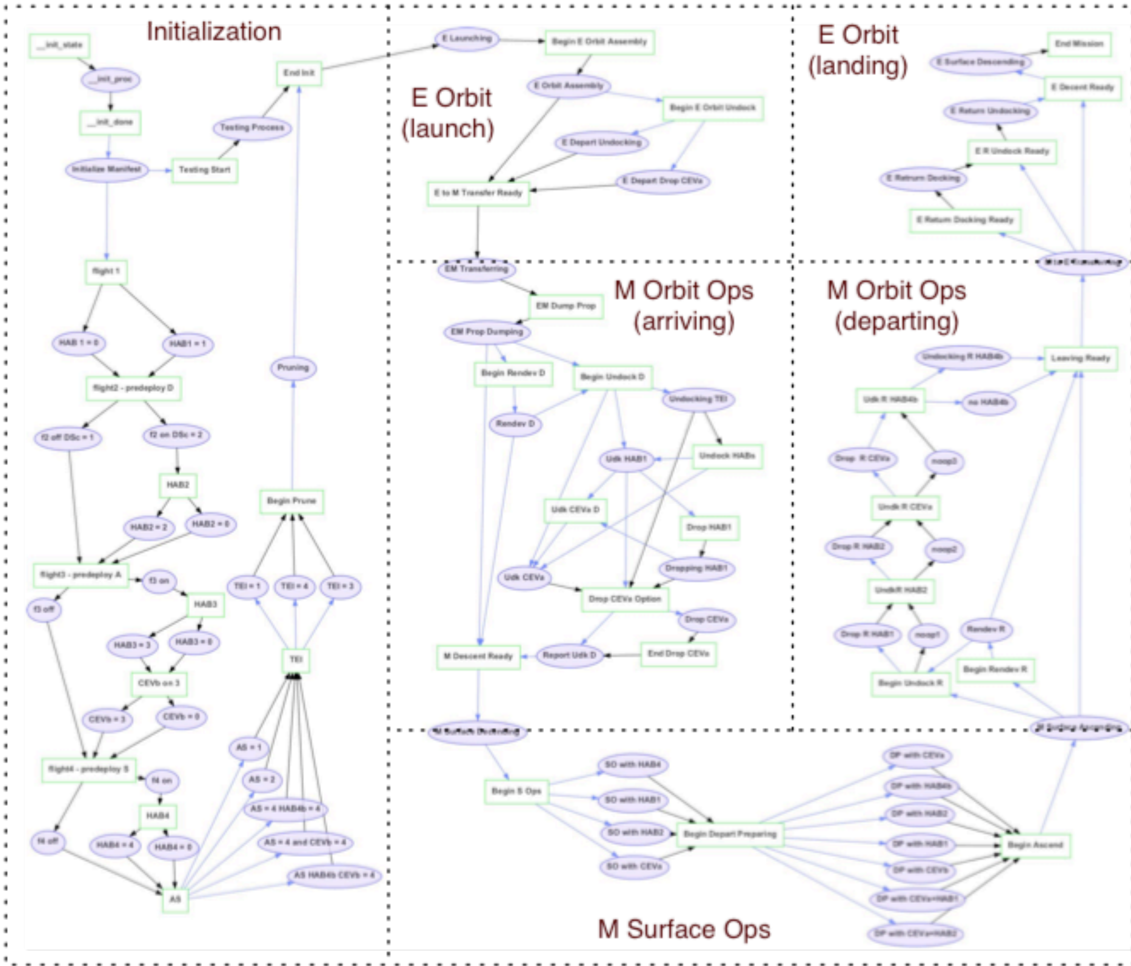


Figure 2 Object Process Network for M Transportation Architectures

Ed Crawley's[36] needs framework forms the foundation for the idea of stakeholder related benefit metrics. There are several keys ideas listed here, drawn from his ESD.34 System Architecture course.

Crawley defines an architecture as "The embodiment of concept, and the allocation of physical/informational function to elements of form, and definition of interfaces among the elements and with the surrounding context." Formally then, selection of an architecture means choosing a concept, determining requisite functions, identifying possible forms, allocating functions to forms, and defining interfaces between elements and interfaces with the architecture. The contention that stakeholder benefit analysis could help select an architecture is possibly related to the following subset of those functions:

1. Determining requisite functions. Functions must alter an attribute of the operand in order to deliver value. This suggests value is to some extent driven by change, rather than steady processes.
2. Selection of forms which impact cost. Crawley defines value as benefit at cost.

3. Defining interfaces with the surrounding context. This was the genesis of the idea that the organization produces outputs, the sum total of which must capture all value delivery. Nothing which remains internal to the organization actually delivers value.

Crawley then identifies the concept of the need, which must be satisfied by the outputs of the architecture. The key here is that needs satisfy beneficiaries, which are distinct from stakeholders. Beneficiaries are those parties that receive benefit from the organization, but do not necessarily contribute resources or hold a stake in the organization. A beneficiary for NASA could be the Department of Agriculture, which may use the results of space-based terrain mapping, but is not dependent on NASA in order to accomplish its mission, nor does it contribute to NASA's mission.

Finally, Crawley distinguishes between solution-specific and solution-neutral functions, as shown in the diagram below. Leveraging the concept of solution-neutral functions enables us to define needs and their relationship to the architecture, without picking a specific architecture. This is one of the necessary ingredients for using a Koo's approach to architecting for benefit considerations.

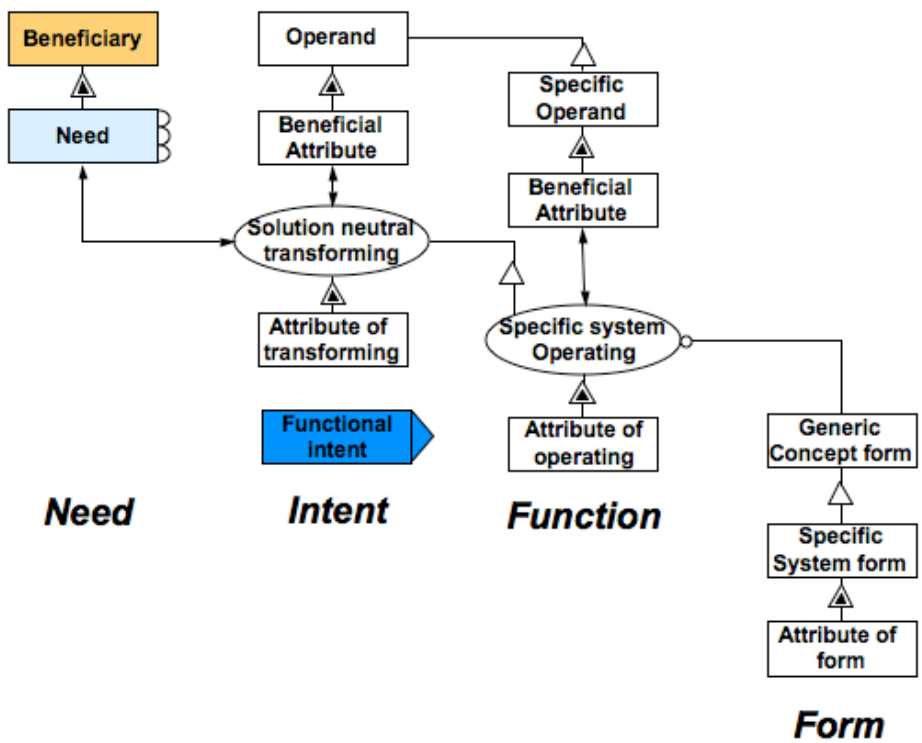


Figure 3 Crawley's Decomposition of Needs to Form

(Adopted From Crawley ESD.34 Course Notes)

The next contributors are Geilson Loureiro[37] and Eric Rebentisch [Rebentisch], who created the first instantiation of the NASA value model. Among other activities during the NASA CE&R project, they created a series of black box models of stakeholders, concretizing the ideas of needs as inputs and organizational interfaces as outputs. These black box models were the linked together, connecting outputs to inputs, forming 'value flows' and creating a network model of value. The implications and benefits of these decisions were not immediately expressed, and are discussed later in this thesis. Although there was a desire to use a quantitative framework to evaluate these feedback loops, one was not realized, thus creating the opportunity that this thesis partially fills.

Additionally, Loureiro and Rebentisch helped create the concept of proximate metrics, based on these value flows. Proximate metrics were the first set of benefit metrics, but were not directly linked to organization's outputs (as is done later in this thesis). Finally, Rebentisch and Crawley expressed a desire to rank the benefit to each stakeholder separately, forcing the recognition that the contributions to value for many stakeholders are not well modeled.

The final contributor is Sandro Catanzaro[38], who conceived of a reciprocal model whereby an organization should value its outputs based on their ability to generate the organization's input. Catanzaro constructed a probabilistic model that attempted to incorporate the uncertainty associated with value mapping. Furthermore, Catanzaro took the approach of modeling many cycles, enabling a differentiation between short term value and long term value. His model captured detail in terms of the accomplishment of possible objectives, but then approximated stakeholder interactions by single pairwise comparisons, as shown in the diagram below in the 'Stakeholder Interactions' matrix. Catanzaro assumed that all stakeholders can provide all resources, each to a different extent.

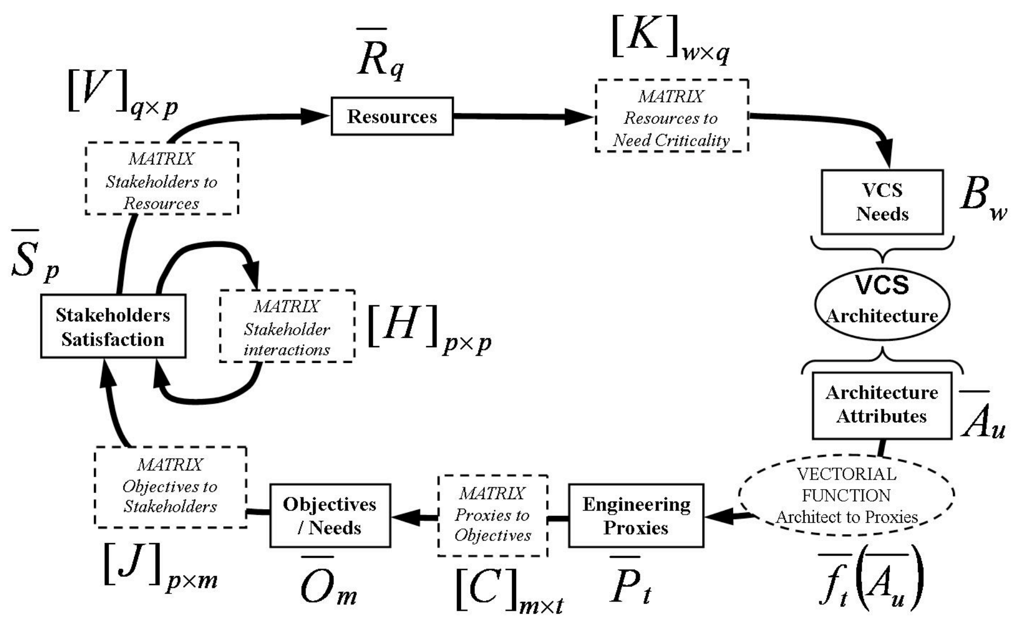


Figure 4 Catanzaro's Stakeholder Architecture Model

Catanzaro's model provides a number of important foundational concepts, but leaves many open research directions. While his association matrices provide a general solution, many of the pairwise associations are not used, incurring significant computational and complexity costs in the process. His use of a probabilistic model assumes that the uncertainty can be captured from a spread relevant transactions, which are not necessarily available. Additionally, his study focused on a disparate and incomplete set of decisions, framed in terms of goals rather than grounded in previous work by Crawley on needs, thus leaving out a number of interaction effects.

Therefore, I identified opportunities to create a complete model, formalize the rules by which a stakeholder model is created, simplify the modeling layer to bring out relevant feedback loops, and assess the architectural implications of this work. Each of these opportunities is explored in turn in the subsequent chapters.

3. Value Loop Thinking

So far, I've motivated the idea that benefit is not captured or analyzed in current architecting processes, and I've worked through some of the academic considerations which would be desirable to capture in a benefit model.

In this chapter, I present a methodology that ties many of these considerations together. I introduce a numerical method for evaluating the strength of stakeholder feedback loops, with a view to prioritizing stakeholders and identifying important loops. Specifically, I provide answers to the following questions:

- ☒ Determine how to interpret Kano levels
- ☒ Determine how to interpret influence around a loop, through an agent
- ☒ Introduce competition in loops
- ☒ Derive scheme to incorporate Kano, importance, competition
- ☒ Determine how to best extract these three data from stakeholders

3.1. Building a Value Flow Model

In order to address a number of concerns relating to the first instantiation of the value model, a systematic reconstruction was undertaken. Specific attention was paid to connectivity (ensuring all inputs were derived from an output somewhere else) and to explicitly identifying modeling decisions that determine the amount of detail captured in the model. For completeness, the full process for constructing the model is given below. The conjugation 'we' is used throughout Section 3.1 to indicate that the majority of the underlying work was a team effort, as described in Section 2.3 Previous MIT Work.

There are four main steps to constructing this model, each of which is discussed in more detail below.

1. Identifying Stakeholders
2. Discovering Stakeholder Needs
3. Modeling Stakeholders
4. Creating Value Flows

Once the model has been created, I will discuss qualitatively which aspects of stakeholder behavior I want to capture, and will then present a numerical methodology that captures this behavior quantitatively.

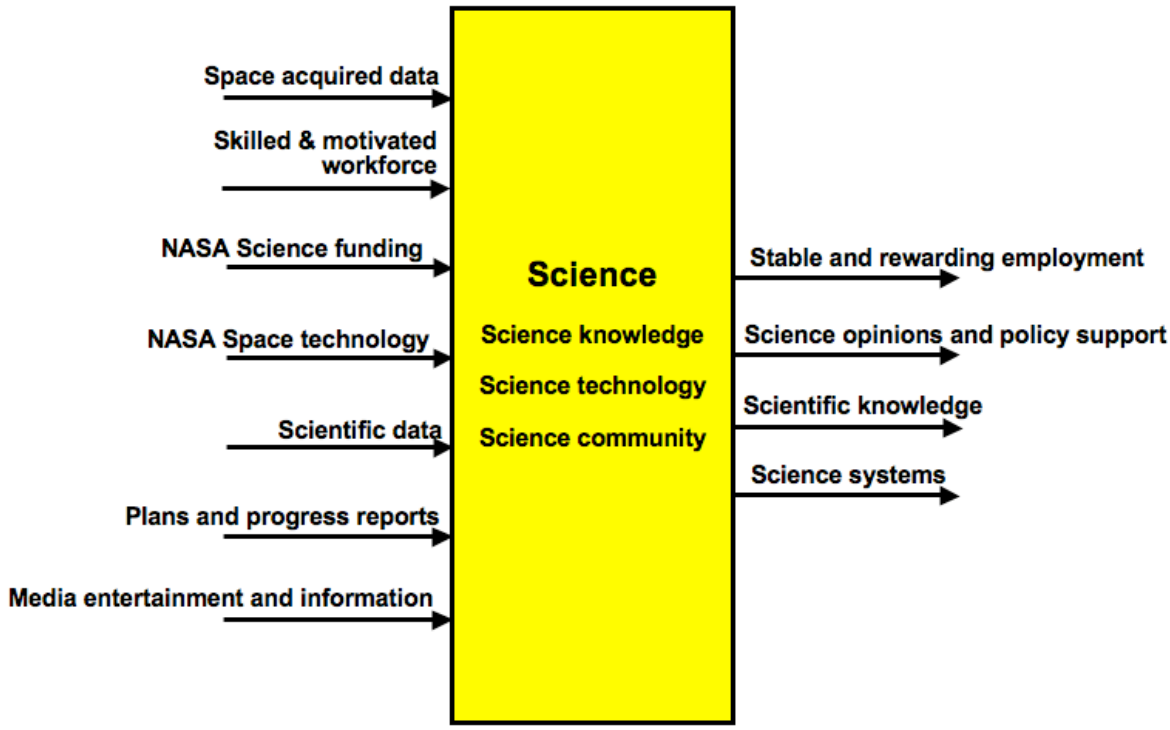
Identifying Stakeholders

My definition of stakeholders requires that stakeholder have the possibility of affecting the organization and receiving some sort of output from the organization. Therefore, sketching all parties that can affect the organization is the first step in identifying stakeholders. Listing all of the outputs of the organization and who they flow to is the second step. One then needs to reduce these two sets to the groups that meet both criteria.

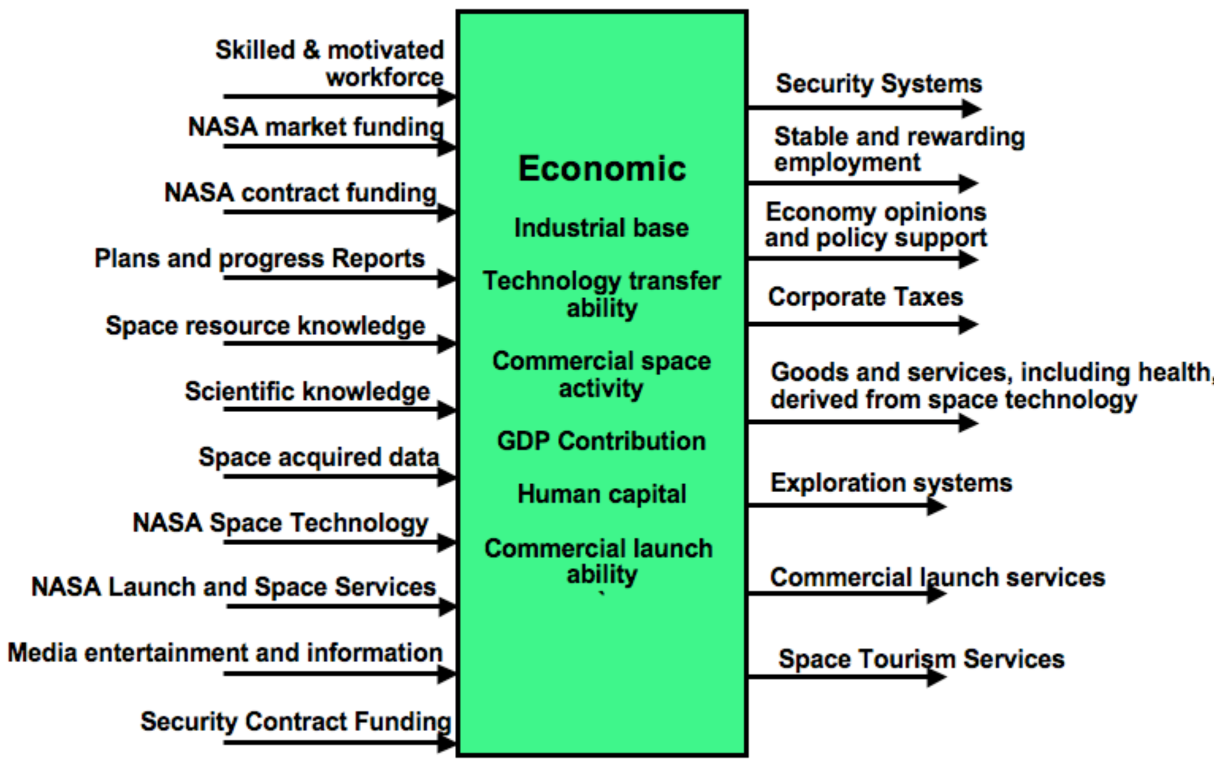
Generally, the difficulty with stakeholders is not in defining the largest possible set. Corporate mission documents, legislation and past transaction histories all provide suggestions as to who could be considered a stakeholder. The real difficulty is applying one's definition of 'affecting the organization' and 'receiving output from the organization' consistently.

For NASA, stakeholders are identified by answering the question: *'who are the stakeholders of the space exploration systems of systems to whom benefit might flow?'* Sources for answering this question were: the Constitution of the United States, the Space Act of 1958 as amended[39], the Vision for Space Exploration (VSE)[40] as well as working group discussions.

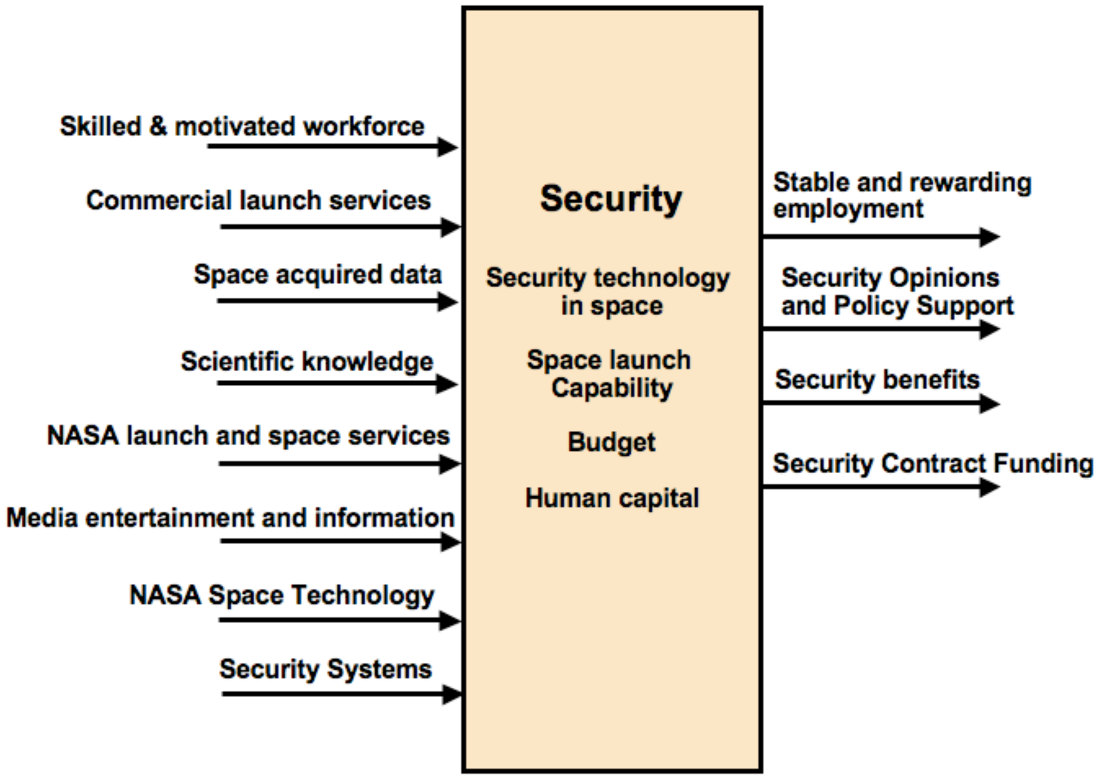
Three of the major groups are explicitly mentioned in the top-level objective in the Vision for Space Exploration: *'The fundamental goal of this vision is to advance U.S.* **Scientific***,* **Security***, and* **Economic** *interests through a robust space exploration program.'* The Vision for Space Exploration also implicitly notes the **US People** as a benefactor of space exploration: "*A significant human component can inspire us – and our youth – to greater achievements on Earth"*. I broke out **Educators** as a separate stakeholder, to explicitly capture this commitment to youth and training. The **Media** was also added to recognize that there is typically an intermediary between the NASA and the US People, which has the potential to influence value. The **Executive and Congress** were added as the constitutional agent for the US People. Finally, **International Partners** are included for their mention in the Space Act of 1958, which mandates that NASA "shall make every effort to enlist the support and cooperation of appropriate scientists and engineers of other countries and international organizations". In the Vision for Space Exploration, international participation is encouraged to the extent that it "further[s] U.S. scientific, security, and economic interests". The eight stakeholders groups, plus NASA, are shown in the figure below.

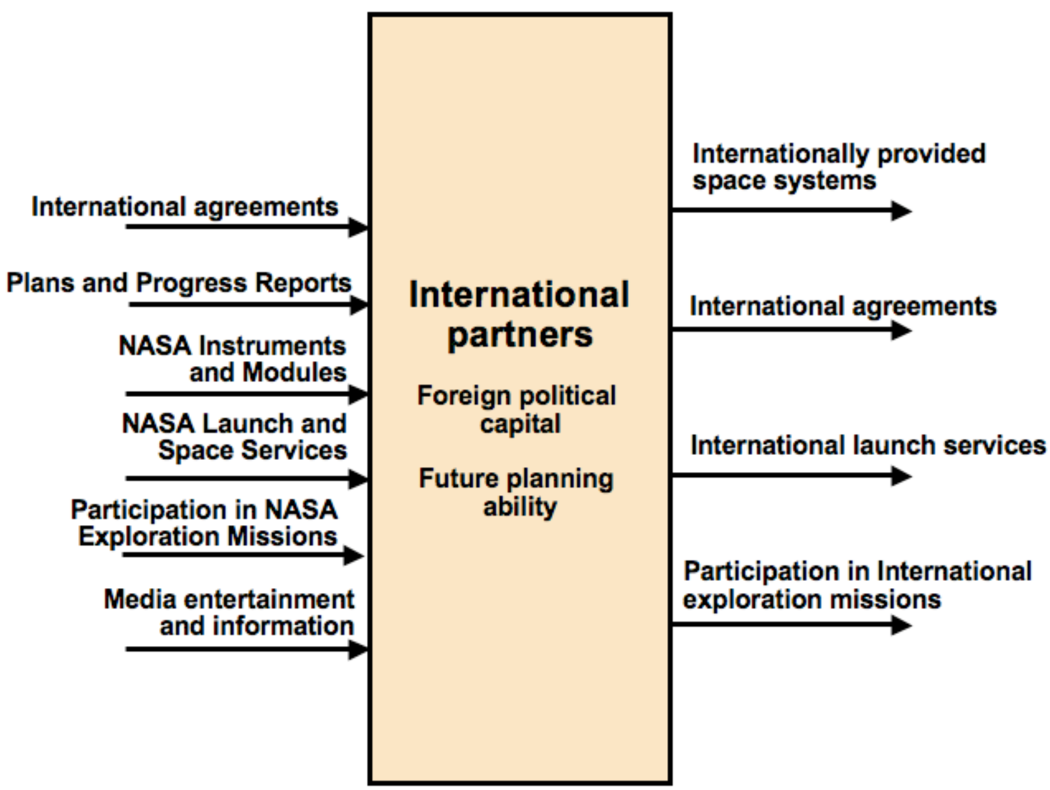


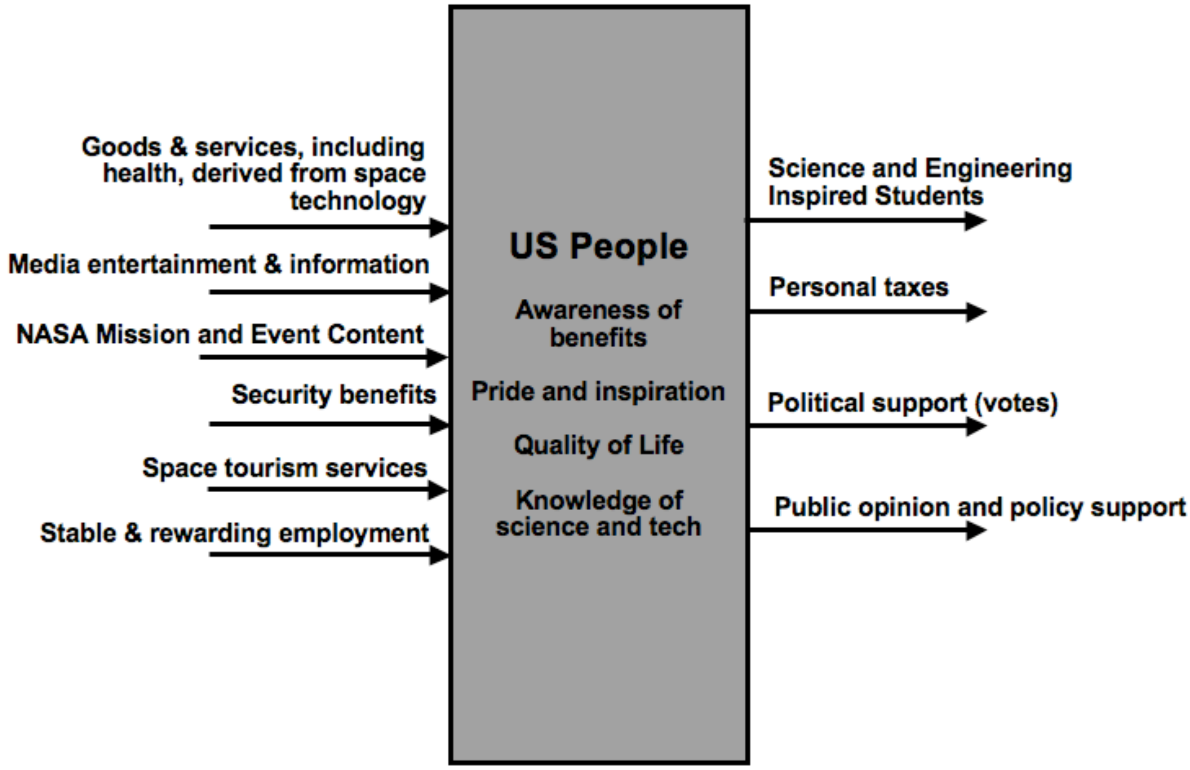
Space acquired data
Skilled & motivated workforce
NASA Science funding
NASA Space technology
Scientific data
Plans and progress reports
Media entertainment and information
Science
Science knowledge
Science technology
Science community
Stable and rewarding employment
Science opinions and policy support
Scientific knowledge
Science systems

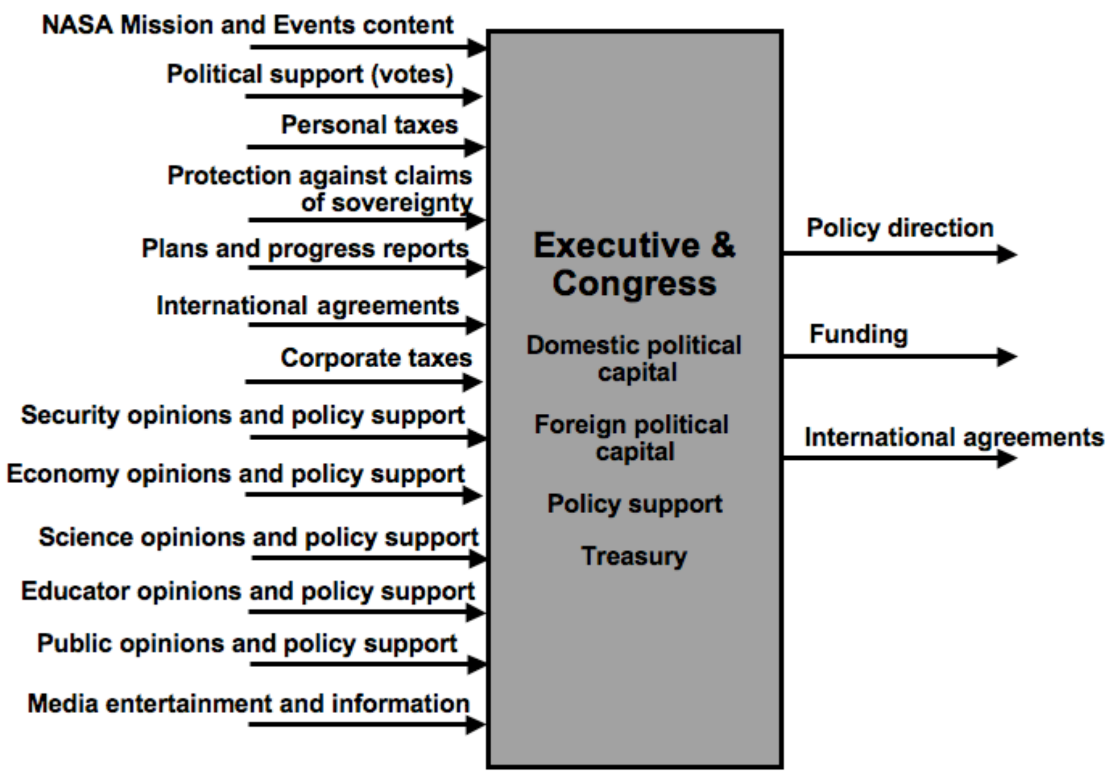


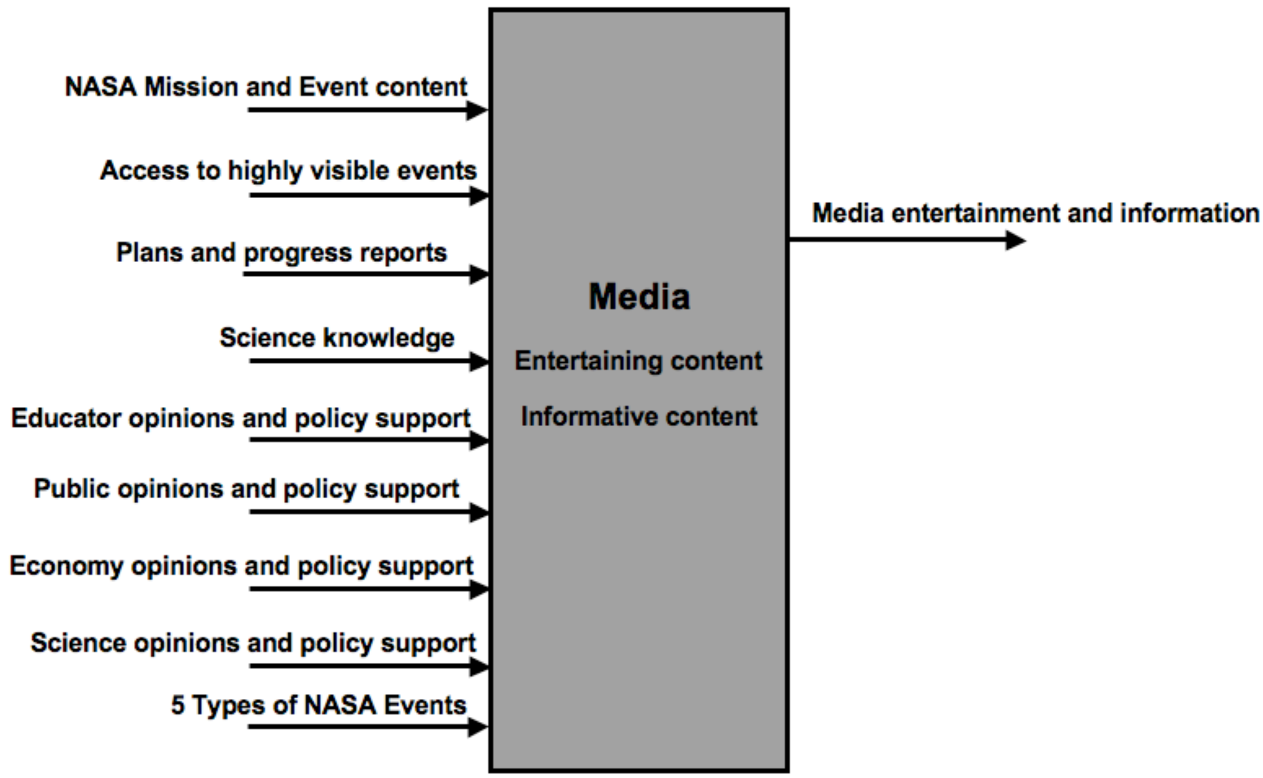
Skilled & motivated workforce
NASA market funding
NASA contract funding
Plans and progress Reports
Space resource knowledge
Scientific knowledge
Space acquired data
NASA Space Technology
NASA Launch and Space Services
Media entertainment and information
Security Contract Funding
Economic
Industrial base
Technology transfer ability
Commercial space activity
GDP Contribution
Human capital
Commercial launch ability
Security Systems
Stable and rewarding employment
Economy opinions and policy support
Corporate Taxes
Goods and services, including health, derived from space technology
Exploration systems
Commercial launch services
Space Tourism Services

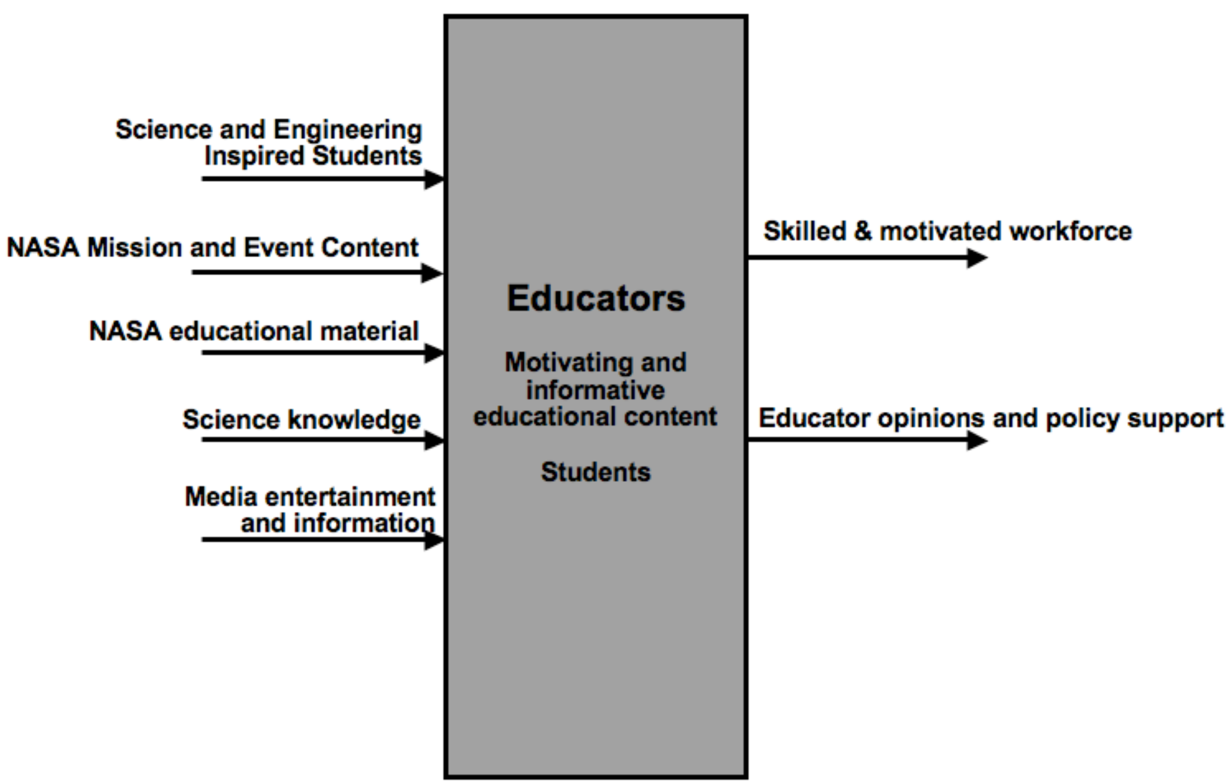

Skilled & motivated workforce
Commercial launch services
Space acquired data
Scientific knowledge
NASA launch and space services
Media entertainment and information
NASA Space Technology
Security Systems
Security
Security technology in space
Space launch Capability
Budget
Human capital
Stable and rewarding employment
Security Opinions and Policy Support
Security benefits
Security Contract Funding


International agreements
Plans and Progress Reports
NASA Instruments and Modules
NASA Launch and Space Services
Participation in NASA Exploration Missions
Media entertainment and information
International partners
Foreign political capital
Future planning ability
Internationally provided space systems
International agreements
International launch services
Participation in International exploration missions


Goods & services, including health, derived from space technology
Media entertainment & information
NASA Mission and Event Content
Security benefits
Space tourism services
Stable & rewarding employment
US People
Awareness of benefits
Pride and inspiration
Quality of Life
Knowledge of science and tech
Science and Engineering Inspired Students
Personal taxes
Political support (votes)
Public opinion and policy support


NASA Mission and Events content
Political support (votes)
Personal taxes
Protection against claims of sovereignty
Plans and progress reports
International agreements
Corporate taxes
Security opinions and policy support
Economy opinions and policy support
Science opinions and policy support
Educator opinions and policy support
Public opinions and policy support
Media entertainment and information
Executive & Congress
Domestic political capital
Foreign political capital
Policy support
Treasury
Policy direction
Funding
International agreements


NASA Mission and Event content
Access to highly visible events
Plans and progress reports
Science knowledge
Educator opinions and policy support
Public opinions and policy support
Economy opinions and policy support
Science opinions and policy support
5 Types of NASA Events
Media
Entertaining content
Informative content
Media entertainment and information


Science and Engineering Inspired Students
NASA Mission and Event Content
NASA educational material
Science knowledge
Media entertainment and information
Educators
Motivating and informative educational content
Students
Skilled & motivated workforce
Educator opinions and policy support

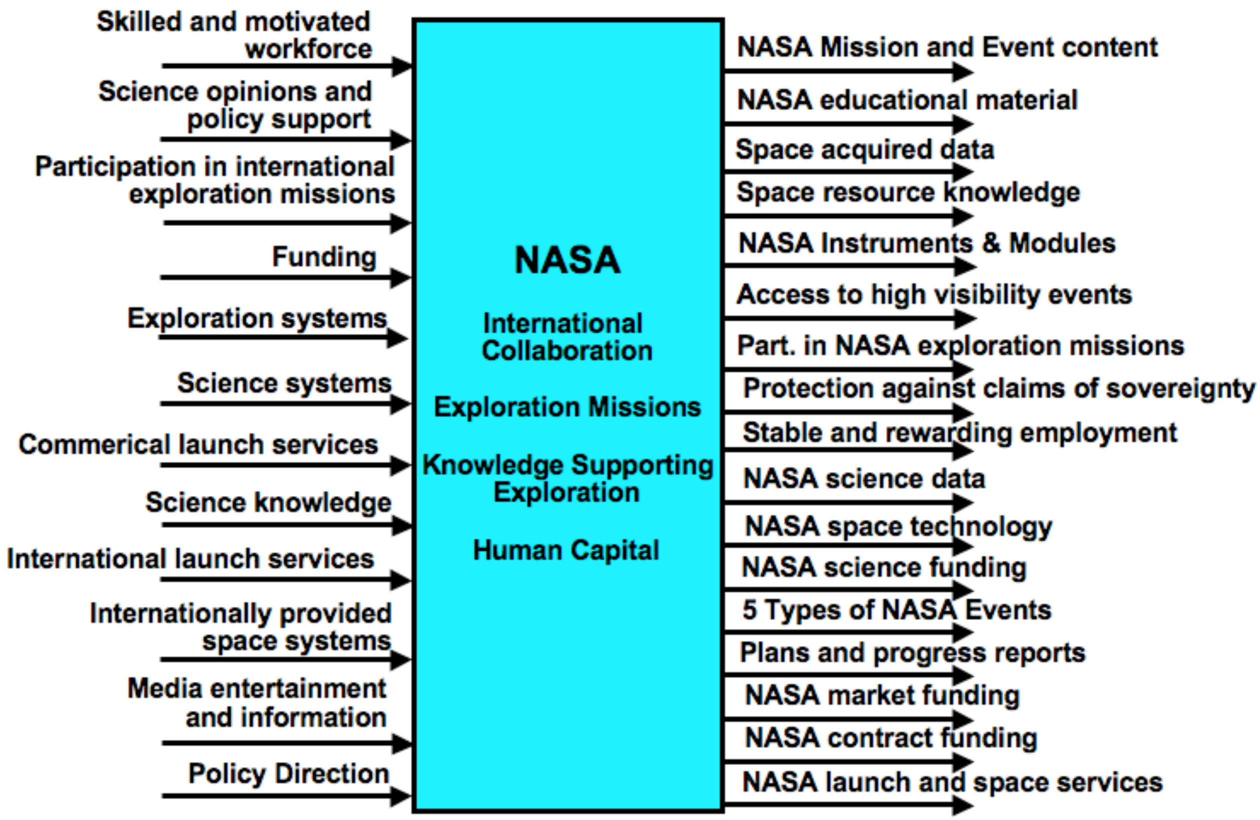


Figure 5 Stakeholder Input Output Diagrams

Interestingly, the Space Act of 1958 explicitly identifies Mankind as a stakeholder: "for the benefit of all mankind", but Mankind is not mentioned in many recent documents, including the Vision for Space Exploration.

The table below provides a more in depth definition for each stakeholder.

Table 1 Stakeholder Definitions for NASA Model

Stakeholder	Definition
Economic	The for-profit actors that interact directly or indirectly with NASA. Examples include contractors and aerospace firms
Educators	The individuals and institutions that comprise the US educational system, from the primary level to universities.
Executive and Congress	The leglislative and executive branches of the US government. This include the individuals, committees, agencies other than security, and advisors
International Partners	The foreign governments, national space agencies, and foreign contractors could potentially interact with NASA.
Media	The firms responsible for the acquisition, composition, and distribution of news and entertainment internationally which could potentially cover NASA.

NASA	The US government agency which is tasked with the civilian use of space, including headquarters and centers.
Science	The international body of scientists, communities, and institutions which perform or advise on science within NASA's mandate
Security	The US government agencies, civilian and military, whose primary purpose is the provision of intelligence, or offensive and defensive capabilities.
US People	The US population, not limited to those of voting age.

These eight stakeholder groups are classified into four types, identified by color in the figure: public (grey), security (pink), economic (green), science (yellow). These types were created to explicitly identify that some stakeholders, such as educators and media, are intermediaries in the process of delivering value to the US People.

The level of aggregation chosen for stakeholder groups determines the level of detail of the remainder of the model. Given that the number of possible links in the system scales quadratically with the number of nodes, one should chose the minimum number of stakeholders that will capture the important outflows of the value creating organization. For example, I abstracted the military space interests as "Security", despite the fact that it is made up of the 3 branches of the military plus associated agencies, because they all have similar needs from the NASA perspective. The key is to converge on a level of detail that is uniform through the system, and that communicates the important concepts.

It is important to make the distinction between stakeholders and beneficiaries. Beneficiaries are those parties that receive benefit from the organization, but do not contribute resources or hold a stake in the organization. A beneficiary for NASA could be the Department of Agriculture, which may use the results of in-space terrain mapping, but is not dependent on NASA in order to accomplish its mission, nor does it contribute to NASA's mission. It is desirable to exclude beneficiaries who are not stakeholders in this analysis, because they will never close the value loop back to the value creating organization. Beneficiaries often form a superset of stakeholders – I took the approach of identifying all beneficiaries, and then culling the list to remove those that are not stakeholders, using the filters mentioned above.

Having identified the stakeholders, the next step is to capture their needs, in order to determine how value is created.

Discovering Stakeholder Needs

In this section, we determine the needs of all stakeholders. This process will help identify conflicts between stakeholders, to the extent that their needs conflict or are synergistic. Additionally, needs form the true metric by which an architecture's value to stakeholders is determined.

I used three techniques to elucidate needs.

First, I asked “Which inputs were required by the stakeholders?”. For example, scientists clearly require science data, and commercial launch providers (within the economy stakeholder group) need customers in order to generate revenue.

Second, I asked “What are the outputs of the value creating organization, and who they are provided to?”. The question then becomes, what needs are these outputs satisfying? For example, NASA is charged with inspiring the American youth to pursue science and engineering careers, which suggests that the American people have a need to be inspired by exploration. However, it is important that needs are not created simply to match outputs. Those outputs that do not link to true needs do not deliver value – these are an important output of the analysis, and will be treated separately.

Third, I combinatorially paired stakeholders other than the value creating organization, and asked whether there are relevant transactions that play out between them. Understanding which transactions are relevant becomes clearer once the value loops have been identified and labeled, but at this stage, it is best to err on the side of discovering more needs.

Typically, the difficulty is not in listing needs, but rather in culling the list of needs for the independent and salient entries, such that they can reasonably be mapped to stakeholders. Our process generated 81 stakeholder inputs, for a total of 48 distinct needs, ranging from ‘Protecting against foreign claims of sovereignty’ to ‘Attract a skilled and motivated workforce’. These were recorded in input-output diagrams centered on each stakeholder (and the value creating organization), shown in the figure above.

Each of these needs represents a possible requirement on NASA’s architecture. In order to downselect to the requirements that will be satisfied, we have to determine how needs are related to value, which will be accomplished by modeling stakeholders.

Modeling Stakeholders

Having documented all of the needs of stakeholders, the question becomes ‘How are needs related to value delivery?’. I postulate that the delivery of value is often related to the core objective(s) of each stakeholder – the next step is therefore to model the objectives of stakeholders. Our aim here is to explain how and why each stakeholder transforms the inputs they receive (according to their needs) into outputs they produce.

I model each stakeholder using three attributes:

To: An objective function or purpose.
By: A listing of processes and outputs used to accomplish the purpose.
Using: A listing of transferable assets and inputs required to execute the processes

This model has several key ideas embedded in it. First, all stakeholders have different goals, as embodied in the 'To' statements. The outputs of the value creating organization are used to satisfy a range of different stakeholder goals. Second, each stakeholder can be measured relative to their ability to produce the outputs of the processes listed under 'By'. Third, 'Using' highlights the transferable assets and inputs that stakeholders require NASA to provide. These transferable assets and inputs then help define the requirements for NASA's architecture.

For example, I represented the Objective of the US People as 'To attain life, liberty, and the pursuit of happiness'. This suggests that somehow, each input should be related to the objective. For example, 'life' suggests that health must play a role, which reminded us that significant physiology research is conducted by NASA, and should somehow provide value to the US People. An example of a 'To By Using' model is provided in the figure below.

To **attain life, liberty and the pursuit of happiness**

By **producing outcomes, and other outputs, directly or indirectly benefiting NASA, including:**

- **Science and engineering inspired students**
- **Tax revenues**
- **Political support for Executive and Congress (voting)**
- **Policy support for NASA (enabled by knowledge of the assets derived from NASA)**

Using **the following assets directly or indirectly derived from NASA**

- **Goods and services, including health, derived from space technology**
- **Media entertainment and information**
- **NASA mission and event content**
- **Security benefits**
- **Space tourism services**
- **Stable and rewarding employment**

Figure 6 To By Using Model of the US People

The 'To By Using' model is clearly related to the input-output diagrams. The added complexity provided in the 'To By Using' is an exercise provided to help discover additional inputs and outputs, by providing a logical model that links the inputs to the outputs within a stakeholder. One can think of this as a consistency check for the needs derived.

However, there is another important function of 'To By Using' model: it can help to limit the number of input-output combinations. I captured part of this input-output connectivity by listing 'stocks' for each stakeholder on the input-output diagrams. Each stock represents a measure of the satisfaction of a stakeholder objective. For example, I list 'Quality of Life' as a stock for the US People, which is derived from the objectives 'Attain Life' and 'Pursue Happiness'. However, to be clear, these are not System Dynamics stocks, in the sense that they fill up over time with a given rate. Therefore, 'internal assets' is perhaps a more representative term for these 'stocks'.

That being said, the core purpose that internal assets serve in a *modeling* sense is to restrict groups of inputs from groups of outputs. As defined before, loops in this model are created by branching at each node in the network. The more branches are available, the more loops. If all inputs can connect to all outputs, then each outputs represent a possible branch. Internal assets are needed to restrict this input-output connectivity, to ensure that chains of links represent realistic causation.

> **Principle**
> Internal assets restrict the input-output connectivity of a stakeholder model

Therefore, the number and type of internal assets is chiefly a modeling decision. The internal assets I chose for the Science stakeholder are shown below. While I could have theoretically chosen hundreds of internal assets to represent the goals of the Science stakeholders 3 internal assets were sufficient to restrict the input-output pairings to reasonable loop rationales.

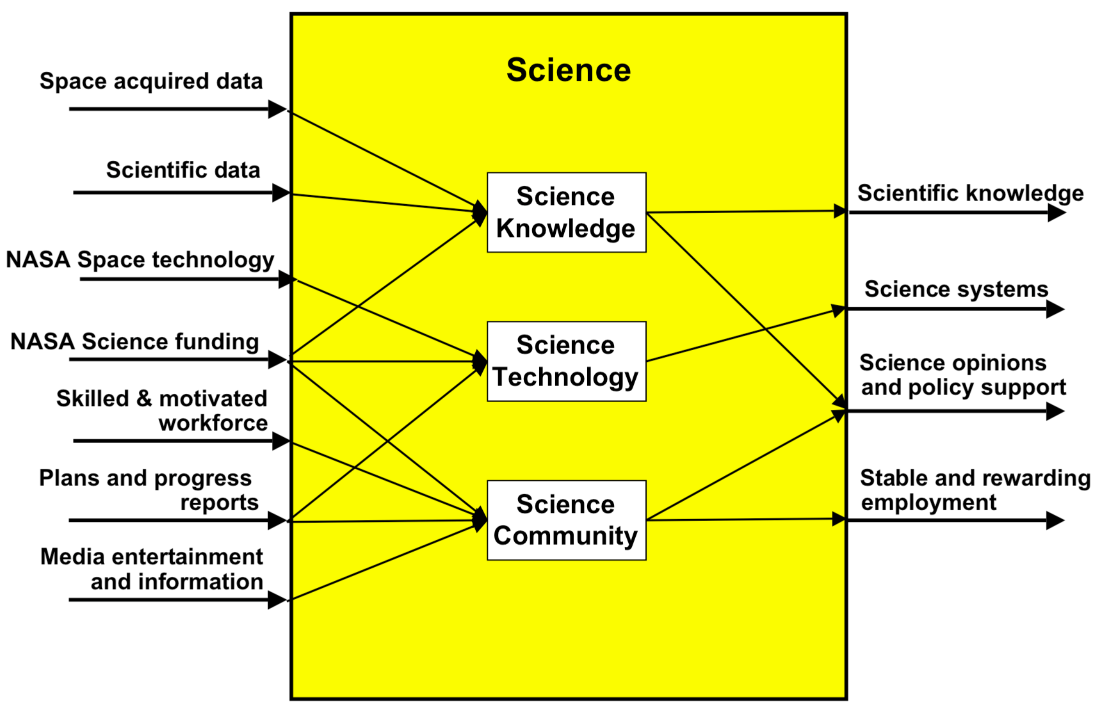


Figure 7 Connectivity of Inputs to Outputs Using Internal Assets For Science Stakeholder

Value Flow : Connecting Outputs to Inputs

Having modeled each stakeholder individually, the next step required is to connect the stakeholders together, using the inputs and outputs that have been discovered.

At this stage, many of the output-to-input (stakeholder to stakeholder) connections have already been formulated in the mind of the modeler, and are easy to connect. For example, having listed 'Science knowledge' as an input to the Educators, it is clear that this derives from an output of the Science stakeholder. The value of this step comes when the modeler discovers inputs that have no matching output, or outputs that do not connect to an input. Given the criteria I used to identify stakeholders, it is not desirable to have unterminated value flows. This dynamic reinforces the iterative nature of this modeling process, where inputs and outputs are deleted and created. This approach represents a systematic process that can help identify areas where value delivery is poorly understood or executed in the systems being modeled.

The key to resolving many of the output-input discrepancies revolves around the level of detail created in the model. I chose a low but uniform level of detail for this initial effort, analogous to a crude macroeconomic model of the US economy. In this manner, I represent the steady state conditions, rather than enter into the complexity of an event-driven model. For example, International Partners provide 'International Space Systems' to NASA, rather than providing the 'Leonardo Module' for a specific flight to the International Space Station. This also facilitates the connection to exploration architectures, in that it recognizes that all architectures should provide the same type of outputs to their stakeholders, and obviates a need to create separate value network models for different architectures. In this sense, the model I created enables a realistic representation of both the Apollo- and Shuttle-era architectures, net of differences in scope between these two and the current VSE.

The resulting value network is illustrated in abbreviated form in the figure below. A select group of value flows is illustrated, as the full set contains 81 links is too complex to illustrate on a small diagram. A full list of all the links in the model is given in Appendix 1, including a description of each link, and where possible, examples of past benefit flows.

It is important to note that in constructing this model, I have introduced a significant bias. I don't illustrate all possible links between any two stakeholder pairs – I illustrate only those that enable us to fill gaps between NASA outputs and NASA inputs. As such, the model is geared towards prioritizing things that are of interest to NASA – we can't necessarily focus on another stakeholder, and ask for the full set of feedback loops that originate and terminate at that stakeholder.

It is useful at this stage to clarify some of the terminology used. I use the term *Value Flow* to mean the connection of an output to an input in the model – it is the provision of value from one stakeholder to another. An individual value flow is uni-directional, and does not necessarily imply a return transaction.

The term *Value Chain* will be used to mean a collection of Value Flows, connected by stakeholders. For example, "NASA provides Science Data to the Science community, which provides Science Knowledge to Educators" would be a value chain starting at NASA and ending at Educators. Typically, in doing so, we are implying some sort of causality, in that participants in the chain have a responsibility or objective to propagate value. A well formed value chain should be explainable in terms of an obligation or incentive connected to the 'To' statement of the stakeholder at that link in the chain. For example, the reason Science creates science knowledge from science data is related to Science's objective 'To create new scientific knowledge and thought'.

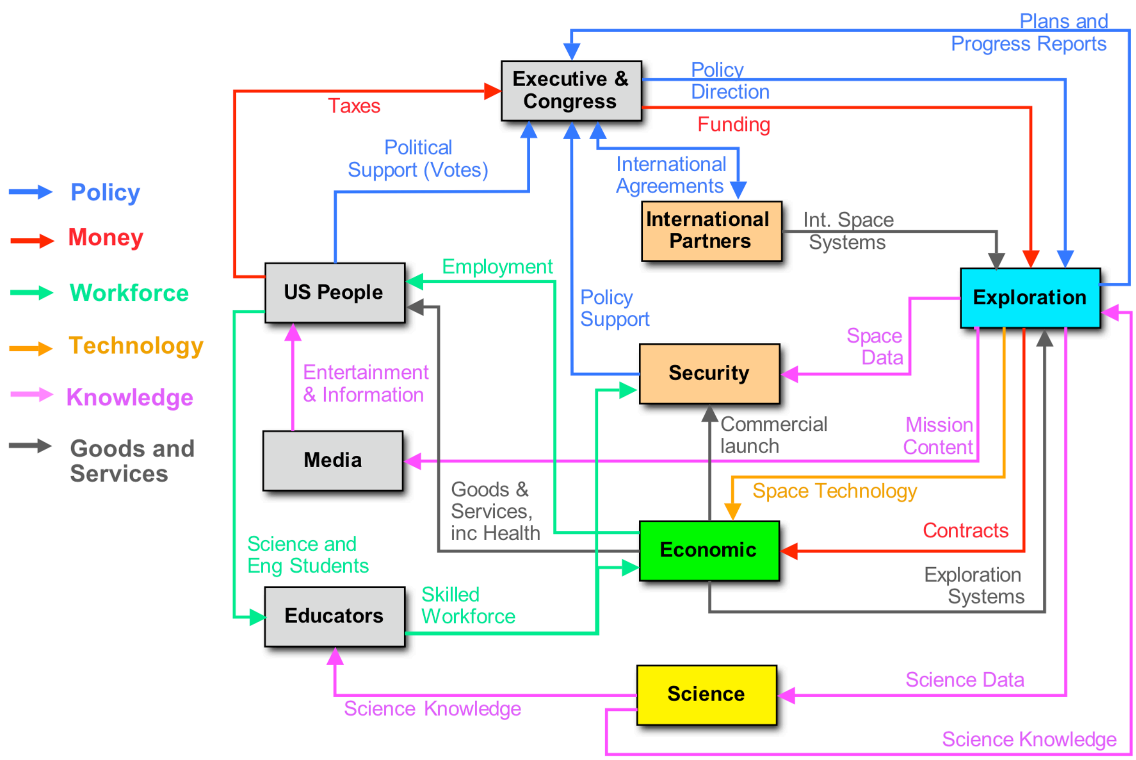


Figure 8 Value Network Diagram (Not All Links Shown)

Finally, I use the term *Value Loop* to denote a Value Chain that returns to the starting stakeholder. Value loops are at the heart of this mapping exercise, in that they illustrate which stakeholder needs are satisfied by strong feedback loops, and which needs are not well satisfied. An example of a loop is "NASA provides inspiration to the US People, who provide political support to the Executive and Congress, who rewards NASA with funding". By building the model up from a series of value flows, the process fosters creativity in loop identification, in that we can examine many possible chains of value flows to determine if they help explain real behavior. For example, by combining value flows I created the loop: "NASA provides launch contracts to the Economic community, which provides launch services to the Security community, who in turn could provide support for NASA to the Executive for NASA funding". This stimulated the idea that that the Economic community has a commercial launch industrial base, such that NASA purchasing launch services indirectly helps the Security community's need for launch services. However, not all combinations of value flows yield realistic value loops. An example of a less useful loop would be "NASA provides Space Technology to the Security community, which as a result provides Security Contracts to the Economy", because there isn't a causal link between Space Technology and Security Contracts.

Notice that much of the behavior in this model appears to be determined by these loops, rather than by direct transactions between actors. This is a reflection of the *indirect benefit* that characterizes public complex systems. I will investigate the indirect nature of this benefit in much greater detail through the thesis, but it is important to note up front that this begins with value loops.

Principle
Indirect benefit delivery forces consideration of value loops over simpler transaction models.

It is worth spending a moment to reflect on how many loops there are here. Given that I defined limited input-output connectivity using internal assets for each stakeholder, not all flows can trace to all other stakeholders in the network. However, what I haven't done is define if inputs are required simultaneously. Therefore, if two inputs connect to one output, then there are two chains create from that one output. This is desirable from a theoretical perspective, given that we are searching for independent pathways through the network to achieve maximum influence. However, it also means that we will have lots of loops, many of which will differ by as few as one link.

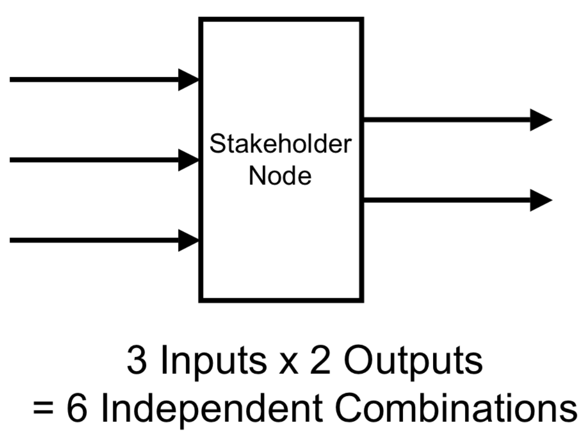


Figure 9 Combinatorial Input Output Pairing

I categorized individual value flows into 6 categories, in order to examine whether most value loops are constituted of similar flows. The six categories represented in our model were:

1) Policy – Flows that relate to the motivation or transaction of policy decisions. Ex. Political Support, International Agreements.
2) Money – Flows that represent funds changing hands. Ex. Corporate Taxes, NASA Market Funding.
3) Workforce – The flow of employment and job-related expertise between different stakeholders. Ex. Skilled Workforce, Stable and Rewarding Employment.
4) Technology – Sharing of technology between stakeholders. Ex. Space Technology flowing from NASA to the Economy.
5) Knowledge – The transmission of knowledge from one stakeholder to another. Ex. NASA provides Space Resource Knowledge to the Economic community.
6) Goods and Services – The transaction of actual technical goods and services. Ex. International Space Systems.

Note that the majority of the value loops are composed of several types of flows. This implies that there are several conversion steps that happen within a stakeholder to transform, for example, a skilled workforce input into exploration system output. These transformations are accomplished by the organization's business and cultural processes.

First, it is possible that this makes it more difficult for those inside an organization to understand which inputs are critical to which outputs. In particular, where one group is responsible for receiving inputs, and a second is responsible for using those inputs, then the perception within the organization might well be that 'of course we own X', especially where there are few communications lines between those on the 'client' side, and those on 'inside'. This problem is exacerbated when those on the output side aren't the same 'client' facing people as from the input side.

Second, it is possible that this is one of the phenomena that makes it more difficult to conceive of value loops, in the sense that connections between stakeholders are less tangible when there is a conversion of flow type. There is certainly an interaction between conversions of flow type and visibility down loops, in the sense that a loop with no conversions will be easier to understand, even going back 3 or 4 links, compared with a loop with multiple conversions.

Principle
Network diagrams can help represent and book keep complex value flows characterized by indirect value delivery

The ability of players in the system to visualize internal connectivity and loops in the system has a direct impact on their understanding of their role, in that it can mean the difference between treating troubles as 'exogenous' and 'random' vs. 'endogenous' and 'controllable'.

Key Modeling Decisions

Having now constructed the value model, there are several questions that arise as to how the model reflects the theoretical underpinnings expressed earlier, and as to how I created logically consistent flows. I focus on the theory questions first, and then treat the practicalities of the implementation second.

There are four main questions which arise from the theory:

1. Does each need have a corresponding stock?
2. Are operands identified in the stakeholder network?
3. When does the absence of a flow create benefit?
4. What happens when the physical flow travels in the opposite direction from the benefit?

1. Does each need have a corresponding internal asset?

Rigorously, each need should be satisfied by a Solution Neutral Process operating on an operand. The reader will recall that needs were primarily discovered in this context by examining flows, not internal assets. It was easier to discover needs through flows, because flows are more concrete than stocks in many cases. For example, it is much easier to visualize Stable Employment than it is to visualize Quality of Life.

However, rigorously, we have to define needs as levels of the internal assets, and flows as the Solution Neutral or Solution Specific Processes that satisfies those needs. In this manner, the attributes of a process map directly to the attributes of a flow, some of which we list directly on the flow. For example, I show <u>Stable</u> Employment, where Stable is an attribute of Employment. Not all relevant attributes are listed, as this would create an unmanageable level of detail. Rather, where a single attribute is central to the value of the flow, it is shown in the model.

While I have now define all needs as having associated internal assets, it is worth noting that not all needs of all stakeholders are represented in this model – only the needs which NASA may directly or indirectly have the ability to influence are captured.

2. Are operands identified in the stakeholder network?

Operands are the objects which are modified by processes. It is the change in state of the operand that satisfy the needs of stakeholders, as shown in Figure 3.

I believe that one of the most common types of operand in the model is an individual within a stakeholder group. It is individuals that are 'modified' when NASA provides employment to the US People, and it is individuals that satisfy the need for a Science Community.

On the whole, operands have not been identified through this process. Identifying operands would be the key step involved in creating actual stocks over internal assets. For example, where I currently show NASA Contracts influencing the Economy's Industrial Base. What operands would have to change to create value to the Economy? The available heavy machinery, corresponding production lines, and the organizational processes for defining requirements, to name a few. If these operands were explicitly identified for all processes (read flows), then we could begin to think about the mapping of operands to stocks for the satisfaction of needs.

3. When does the absence of a flow create benefit?

I introduced a significant bias in framing the benefit in positive terms for this model. For example, I show "Science Opinions and Policy Support" between Science and the Executive & Congress, rather than "Science Opinions and Policy Advice".

The flip side of this positive bias is that sometimes the absence of a flow creates a benefit. For example, the absence of launch vehicle explosions helps create a sense of trust in NASA. Therefore, 'absence of a negative flow' can be equivalently represented as a positive flow. There are three modeling techniques I could use to represent this information:

a. Show a negative flow like "exploding launch vehicles"
b. Show a positive flow like "absence of exploding launch vehicles"
c. Show the action that is more closely linked to the benefit, like the proclamation of safety by a leader

On the whole, I have erred on the side of representing flows that correspond to physical or informational objects. For example, I show Manned Exploration Events and Media Content, rather than Inspiration flowing to the US People. This would suggest that I represent the negative flow.

The answer depends on what we want the model to represent.

If the model is constructed to demonstrate the benefit the organization creates, then the positive representation of the absence is most appropriate.

If the model is constructed to simulate the benefit of an architecture, the again the positive representation or no representation at all would be appropriate.

If the model is constructed to simulate the consequences, positive and negative, of the architecture, then the negative flow should be represented.

Finally, in cases where the negative is highly unlikely but the benefit (here trust) is required on a regular basis, it makes more sense to represent the benefit as proclamations by a leader. This would be most relevant to organizational behavior models.

4. What happens when the physical flow travels in the opposite direction from the benefit?

In the context of organizations, there are many examples of benefits that travels in the opposite direction of the physical or informational flow. For example, issuing guidelines to contractors does not produce benefit to the contractors. Rather, the compliance with those guidelines benefits the organization. Situations like this are more likely to occur for policy flows, particularly where power or organizational authority is exercised. This therefore overlaps with the discussion of the negative benefit flows – exercising authority comes with the threat of being fired or demoted for non-compliance.

From a modeling perspective, the difficult thing is that the frequency with which threats are exercised differs from the frequency with which orders are given. I submit that the most representative flow to illustrate is the compliance with the order (because it actually generates benefit, and because it occurs more frequently), noting the order in the title. For example, "compliance with NASA guidelines" flowing from a contractor to NASA. The question of stakeholder threat power is an important one, and will be expanded on later in the thesis.

Practical Modeling Decisions

In the process of creating the model, a number of modeling decisions were made to simplify value loops, in order to make the model easier to understand. The key decisions are described below.

I abstracted the workforce flows by asserting that the US People are the source of science and engineering inspired students. These students are provided to the educators, and then become the source of a skilled workforce. I chose to represent the body of experience within the educators, because it is simpler than representing skilled workforce flows between all actors, and because the educators are the only stakeholder for whom educating the workforce is a central goal. When we add to this the value chain that describes the Economy and Science support for NASA funding in response to stimulating students, we create a value loop termed the "Inspiration Loop". The build up of the industrial base is then captured separately within the Economy.

Universities are cleaved into the research function, which is stored under Science, and the education function, which is stored under Educators. Science knowledge is then passed from Science to Educators, in order to enforce the connection.

Science missions are lumped under NASA, rather than under Science. I show a flow of a Science Funding to the Science community, which returns Science Systems through to NASA. NASA then operates all science missions, return Science Data to Science, who then return Science Knowledge and Science Opinions to NASA.

I show reciprocal international agreements being transacted between the International Partners and the Executive and Congress, rather than directly between the International Partners and NASA. I then require that the Executive provides policy direction to NASA related to these agreements. However, actual Systems are transacted directly between NASA and the International Partners, such as International Space Systems and NASA Instruments & Modules.

3.2. Qualitative Ranking of Loops

Having now constructed a model that is internally consistent, the question becomes: What do we want to evaluate in a loop? Ideally, the goal is to better understand where NASA can act to ensure it receives its required inputs. Does this imply that we should take a controls perspective - evaluating the polarity and the gain of each loop? Conversely, we could proceed on the premise that a weighted average of stakeholder needs will satisfy stakeholders the most, which will in turn return the resources to the organization.

The chief problem here is understanding the agent problem – that is, when you deliver value through an agent, how do you ensure that agent does the job properly? Each stakeholder acts as an agent to other stakeholders, which is why the agent problem is key to understanding how stakeholders decide to produce their outputs, based on the inputs they receive. If we had well defined rules for the translation of inputs to outputs, we might opt for a controls perspective. If there are no rules, then the blind faith approach described above would be more suitable.

The academic framing for the agent problem lies mostly in economics and political science. Economics focuses centrally on aligning incentives for behavior between the principal and the agent. For example, Hermalin[41] investigates the assumption that market competition will lead to fewer agency goods (goods purchased by the agent which don't add value for the principal). To do so, he develops a model to measure managerial purchases of perquisites in a publicly owned company. Other economists look at the effects of debt in reducing agency costs[42] (by restricting the agent's available cash), and at the effects of increased compensation to executive in reducing agency costs[43]. Incentives typically focus on executive compensation structure, including managerial ownership, salary, and bonuses. Many of these models capture manager behavior in terms of utility functions, and agreement between the principle and the agent in terms of single contract negotiated.

The political science literature on agency theory focuses on four sub-problems: information asymmetries between principal and agent, transfer of risk to the agent in exchange for compensation, moral hazard (lack of effort or withholding of information by the agent), and adverse selection (choosing agents that don't have the skills to do the job). These questions are interesting, but less relevant to the problem at hand. Information and risk exchange are relevant to the extent that they inform what inputs are required are for the agent to do its job. Moral hazard is largely a descriptive endeavor, where we are interested in a prescriptive methodology. Adverse selection is not relevant here, given that our level of detail in modeling does not enable us to choose specific agents. However, thinking about this effect more generally, we could think of choosing different paths to influence the beneficiary based on selection criteria of the agent – stakeholders involved along different paths.

What we really want to know here is what aspects of the contract and the actual exchange cause the agent to do their job. On the surface, the economics literature appears more relevant. However, there are two central difficulties. First, in the public sector, we don't have a pure exchange model, with respect to the negotiation of contracts – agent contracts can be themselves loops, or the contract can be legally required or executive orders. Second, many contracts cannot be reduced to a cash transaction. This makes it more difficult to value incentives, or the outcome of those incentive programs in terms of behavior. What we can learn from the economics model is two things:

1. **Importance matters.** The more central the compensation to the agent is to the agent's survival, the more incentive the agent has to complete the task.

2. **Competition matters.** Stakeholders where multiple individual players compete to perform the agent function will give the principal more power, provided the compensation is important to the agent.

On the surface, the political science literature does not appear particularly useful, because it does not develop a generalized agency model. Tests are applied within case studies to determine the extent to which one political actor acts as an agent to another, but those tests are context specific. For example, Moe[44] examines information as a source of bureaucratic power in political environments, as well as sources of political power. His case study focuses on teacher unions, whereby the bureaucrats (teachers) exercise significant political influence, thus weakening top-down political control. McCubbins argues that administrative procedures, such as "decisions procedures and appeals processes"[45] help overcome this effect, as well as the inherent information advantage bureaucrats have over politicians. This specific case study, while it does provide insights, informs one of the individual links our model, not a framework for evaluating all of the agents in the model. The political science does bring up two key insights though:

3. **There is a choice between "Event-driven" vs. "Information Layer" models.** Questions of information asymmetries raised in the political science literature assume that these asymmetries can be modeled or assessed. However, there is a fundamental modeling decision to made, as to whether information, goods and services are actually propagated in the model, or whether multiple real transactions are abstracted as a single 'average transaction value'. While the former is certainly more desirable for its higher level of fidelity and verifiability, it is not always feasible to capture all of these transactions. I decided to pursue an "Information Layer" model, as I wanted to test if one can create useful results without attempt to model specific transactions. However, this means that more labour has to be put into

design modes of verification for the model, because the output cannot necessarily be empirically compared to a real world experiment.

4. **Many principals are actually agents for another stakeholder.** For example, NASA uses the Media as an agent to deliver content to the US People, but NASA itself is an agent of the US Executive and Congress. Therefore, a model has to either provide a global framework whereby individual transactions define relationships between principal and agent, or keep track of who's the agent and who's the principal in each scenario. For the latter, one could imagine a recursive framework that redefines roles through a value chain, but we're still left with a question of defining contracts in some generalized reference frame.

When I put these four insights together, it becomes clear that the best way to get agents to do their job is to provide them with something that is important to them. This classical 'buyer/supplier power' is a simple but powerful predictor of behavior, and one that can spans all different types of transaction. Furthermore, this approach enables a framework built on individual transactions. Competition can then be layered on afterwards, to bias this buyer/supplier power upwards on downwards based on the availability of alternatives in the market.

Therefore, in a generalized exchange, particularly for the delivery of indirect benefit, I have motivated why it necessary to model the behavior of agents in order to understand the behavior of the exchange. The next section will create a quantitative methodology that capture the salient aspects of agent behavior, importance and competition.

3.3. Numerical Methodology

Beauty in things exists merely in the mind which contemplates them

- David Hume, 1742

Having constructed a network model of stakeholders, and having investigated the central dilemma that we face in constructing feedback loops, it is now time to establish a numerical framework for prioritizing loops.

Ideally, this quantitative framework should have the following qualities:

1) Valuation of individual flows, rather than loops as a whole. Given that our aim is to discover which loops dominate, it would not be appropriate to specify those loops up front.
2) Easy computation of loop value based on combination of flow values.
3) Method should enable the valuation of loops having different flow types. For example, how should be able to compare the input of policy direction against the input of funding.

4) Loop valuation should not explicitly depend on loop length. This suggests that a product rule would be favorable over an addition rule.
5) Output range should remain bounded to facilitate interpretation

What does stronger mean? Here, I use Catanzaro's work to define stronger loops as "more likely to enhance the inputs that the organization requires". Therefore, the question I am answering is "Which outputs should I focus on so as to increase my inputs?". Notice that this is closely relate to the question of "Which stakeholder receive the most benefit from a given set of outputs", but not identical, in that I haven't defined rules for propagating benefit among stakeholders. The question of which stakeholder receive the most benefit will be addressed in the Chapter 5 Linking Stakeholders to Architecture.

This method advocates a selfish bureaucracy, in a sense. By valuing stakeholders on their ability to provide resources back to the organization, we're no longer optimizing based on the 'most benefit to the greatest number of people'. This fits with Wilson's assertion of the perpetuating bureaucracy, whose organizational culture acts to preserve the agency in spite of external changes to the conditions which gave rise to its mission [Wilson, p. 74]. In a sense, this is analogous to the principle in economics that individually greedy decisions build the most stable global outcome, and it ignores questions of Nash equilibria (acting in one's own best interest and that of others). Taking a broader perspective, one can argue that the oversight provided by the Executive and Congress is responsible for NASA envelope of action, which leaves NASA in a position to maximize output based on a given input.

We can also ask the question of variability of inputs – if the goal of our modeling process is to determine which path can best be used to influence inputs, we presume that inputs can be significantly modified. This is examined in the following chapter on results.

The reader will recall that I had investigated several methods for capturing stakeholder needs (Kano, Quality Function Deployment, Lean), and had identified several of the types of attributes that metrics for stakeholder need satisfaction capture. In a sense, each of these methods helped define the strength of an individual value flow, with respect to the beneficiary. Therefore, the necessary steps here are to chose a method for capturing needs, determine how to assign numerical values to individual links, and then to find a method for combining links into loops.

Choosing a Method for Valuing Individual Links

I chose to combine Kano's method with an anchored scale for importance, to define the individual link value. Kano's method was chosen over QFD and Lean because it provides a clearer method for prioritizing needs, and also because it comes with a predefined method for collecting stakeholder input.

It is important to recognize that I have made an assumption here – I have moved from using Kano's methodology to rank attributes of a design to ranking the needs satisfied by the design. What's the difference? Whereas attributes refer the solution-specific portion of a design, needs are solution-neutral phenomena, that isn't necessarily linked to a particular past design. Why might this be a concern? The Kano methodology is grounded in questions that require users to rank their satisfaction relative to the presence or absence of an attribute – if they have not previously used a product (solution specific form), then they may have to conceive of a solution-specific form in order to answer the question. Essentially, needs are more abstract than attributes. I think this is reasonable approximation because the same human behaviors of expectation and excitement are prevalent in both cases. However, this means that we'll have to develop methods to ensure that users are referencing realistic solutions.

The chief difficulty in using Kano is that the methodology mixes binary attributes (the car has brakes or doesn't) with continuous attributes (gas mileage). Exciters and Must Haves are much more easily understood for binary attributes, whereas One Dimensional attributes are more easily understood for continuous attributes. The key to unwrapping this problem is that Kano doesn't specify a particular (baseline) level of performance. It doesn't ask "If you have brakes that help you stop from 60km/h in 10m, how satisfied are you?". The functional and dysfunctional questions only reference whether the attribute performance is "good" or "poor".

There are (at least) two approaches to solving this dilemma:

1. Global Approach. Construct utility curves for each stakeholder need, mapping satisfaction as a function of performance. This is both time-intensive, and requires that stakeholders have a good understanding of their projected satisfaction at a number of different levels of performance.
2. Local Approach. Capture the stakeholder's baseline level of performance, how important it is to them, and how their satisfaction varies locally with performance. Less time is required, but a lower fidelity is achieved.

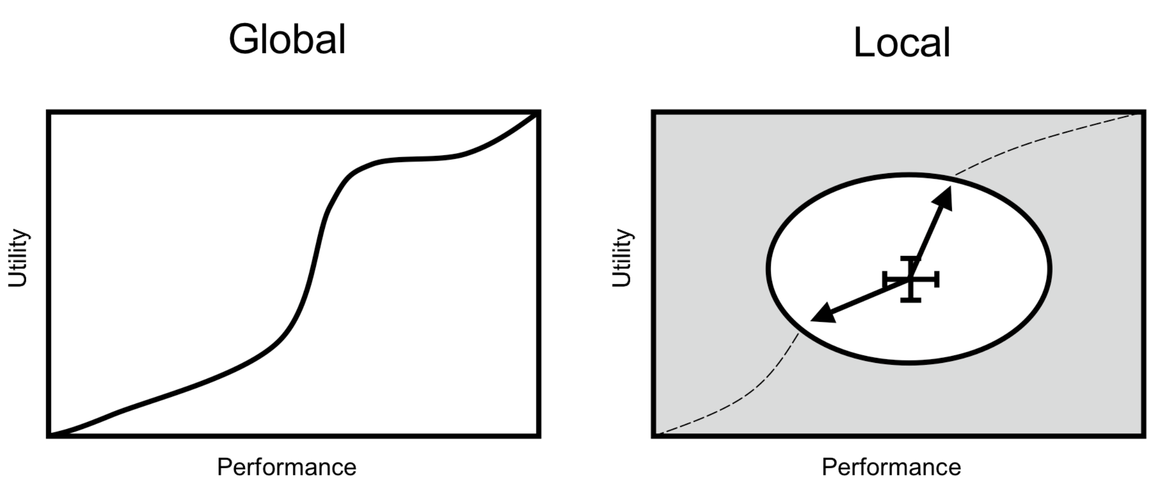


Figure 10 Global vs. Local Approach to Utility Modeling

I chose the Local Approach, because I think it is difficult to define exact levels of performance when referring to flows at our level of abstraction. For example, any definition of performance levels for 'Plans and Progress Reports' is going to involve an artificial scale of performance. Notice that in using this method, I will not use the information on the baseline level of performance. This information will be used later to link architectures to the satisfaction of needs.

In order to create a Local Approach, and in doing so, to solve the Kano 'baseline behavior' problem, I introduce an important scale, which modifies the Kano scale. As these two scales are coupled, I will first discuss the numerical scale for importance, because it is conceptually simpler, and will then discuss how the Kano scale was chosen and combined with the Importance scale to create the desired behavior.

Importance Scale

I used an anchored scale of 'Importance', in addition to the Kano questions. The scale is shown in the table below.

Table 2 Anchored Importance Scale

Not Important	Somewhat Important	Important	Very Important	Extremely Important
0.11	0.33	0.55	0.78	1

There were three decisions made to create this scale:

1. How many points on the scale? If there are too many points (10+), respondents may not use the whole scale, choosing instead to focus on the top 50%, among other problems. Too few points (3 or less) would not reveal sufficient detail about stakeholder needs. I settled on 5 as a reasonable compromise. Note that by using an odd number, I allow the theoretical respondent a 'safe haven' in the middle of the scale. Using a even number would force respondent to decide between 'somewhat important' and 'very important'. While it useful to force respondents to make difficult tradeoffs in order to ensure they are reflecting on their preferences, I felt that there are situations in which it is unrealistic to deny them a middle ground, particularly in a policy environment. Additionally, if I wanted simply a ranked list, I would have chosen another method.

2. Whether or not the bottom anchor corresponds to zero or not? A zero bottom anchor is appropriate for vetting input that stakeholders themselves provide. Given that all the links in the model were created by the modelers, I already felt that the links included were necessary, even if they scored low. The lowest value was essentially chosen as 10%, with some minor other considerations from the Kano scale coupling (to be discussed below) moving it to 11%.

3. Whether to use linear or non-linear spacing? I chose linear spacing, although I contemplated a non-linear scale with multiple values at the high end equal to 1. The choice of spacing doesn't really show an impact until we combine the importance scale with the Kano information, so I will defer until then to discuss it.

With respect to the anchors chosen for the scale, I identify four types of importance anchors:

Benefit / Worth : How important is the benefit flow? No additional prompts.

Vitality : What would happen if you did not receive this input? Is this important enough to bet your business on? Does the inflow represent a piece of the critical path? This introduces an element of risk tolerance, which will vary significantly across actors. Where some actors are constrained with respect to the maximum level of risk they can take on, they would be forced to list almost all items as 'Vital', reducing our ability to discriminate between them.

Replacement : How easily could you replace this flow with a similar one from another source? This begins to include ideas of competition and buyer power, which I wanted to address separately.

Willingness to Pay : If this flow were removed, how much would pay to bring it back? The inclusion of money as a comparative language is clearly not appropriate here, as the focus of this benefit work is enabling comparisons across flow types that cannot reasonably be assigned a numerical value.

I chose to use the Benefit / Worth anchors. I resisted the urge to use the other three, because they mix other ideas in with the specific idea of importance (although they would provide more context).

Kano Numerical Scale

Although I have now illustrated how I modified Kano analysis to include Importance, I haven't illustrated how to derive a single value for each stakeholder need. There is one key parameters that I use to define the relationship between these two scales, which I call the Kano Multiplier.

Kano Multiplier : This number specifies the equivalency between Kano categories at a fixed level of importance. I used a Kano Multiplier of 3, which means that 3 One Dimensional Flows are equal to one Must Have flow. This was a somewhat arbitrary decision, so in the next section, I have included a sensitivity analysis on the Kano Multiplier. One can also think of the Kano Multiplier in terms equivalence at different levels of importance. Using a Kano Multiplier of 3, and our set importance scale, then the following two needs are equivalent:

Table 3 Kano Multiplier Example

	Need #1	Need #2
Kano	One Dimensional (K = 0.33)	Exciter (K = 0.11)
Importance	Somewhat Important (I = 0.33)	Extremely Important (I =1)
Combined Scale	K*I = 0.11	K*I = 0.11

In an ideal world, one would determine the Kano multiplier using conjoint analysis on a subset of the needs, in order to define relative tradeoffs. However, given that this is a global variable (applied across multiple stakeholders), this would require taking some sort of average value across all stakeholders.

Combined Kano-Importance Scale

Given the above information, it is now possible to show what the combined scale looks like. The figure below shows a color mapping of Kano – Importance space.

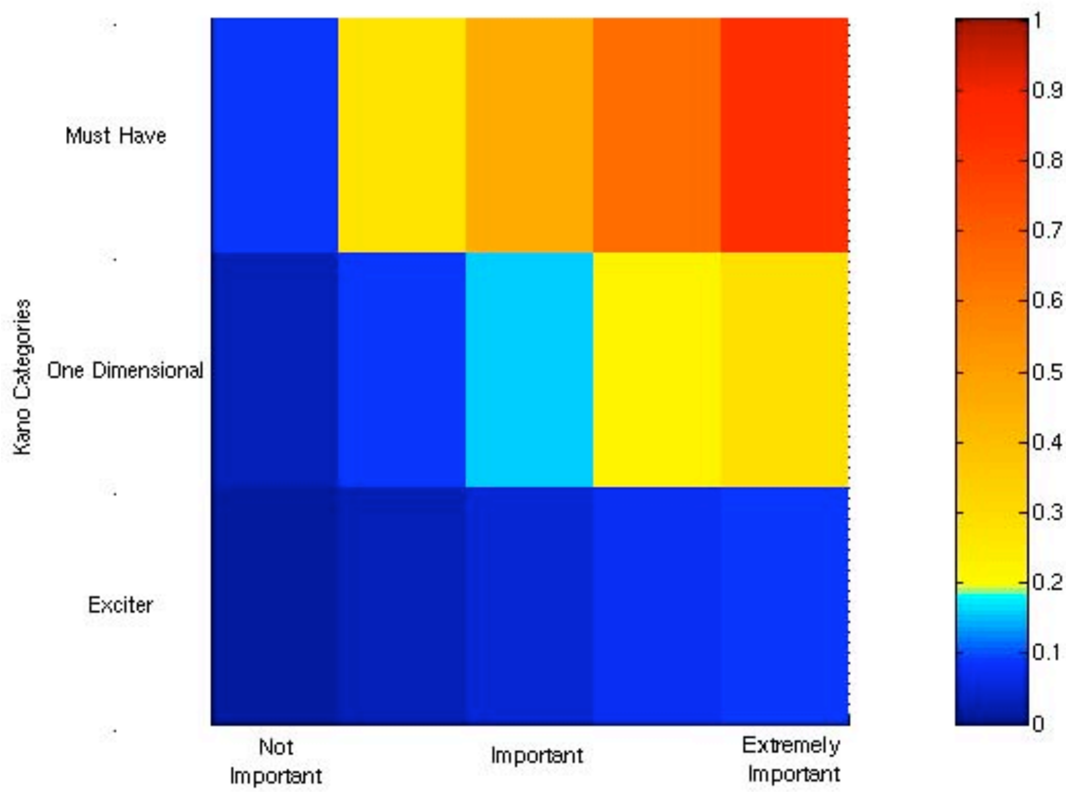


Figure 11 Kano - Importance Surface

There are two possible interpretations of the methodology I've created by combining Kano and Importance information:

1. Importance is fine tuning Kano. We've specified the Kano category, Importance us allows us to rank within a Kano category, and we've also allowed stakeholders to modify the Kano rankings where there are differences in maximum utility across different Kano categories (ex. between One Dimensionals and Exciters).

2. Kano is tuning the Importance ranking. Importance is the primary stakeholder input, but then we weight their preferences by the possibility of detriment. Essentially, this presumes that the respondent doesn't properly account for detriment in answering importance questions, requiring a correction. On a minor note, the presumption of the 'possibility' of detriment requires some assumptions about the uniformity of performance ranges considered across different Kano categories. With a Kano Multiplier of 3, we've used a *heavy* weighting.

Thus far, I've defined a method for valuing individual links. It is useful to step back for a moment to understand that I've only captured a limited subset of Garvin's 8 markers of quality in my method. I argue that perceived quality is included in the method, in that the respondent is aware of the origin of the benefit flow when answering the Kano questions. We could conceivably also use the methodology to define values for the Reliability, Conformance, Durability, and Serviceability of an individual flow, but we would then need a method for weighting between these attributes. The point is that I haven't defined all the attributes of utility because I'm using the Local Approach.

Table 4 Markers of Quality Captured by Kano & Importance

Markers of Quality	Captured by Kano & Importance?
Performance	☑
Features	☑
Reliability	
Conformance	
Durability	
Serviceability	
Aesthetics	
Perceived Quality	☑

Using this link valuation technique, I created surrogate data for each of the stakeholders. An archive of this information is presented in Appendix 1**.** Each link was valued from the perspective of the stakeholder in question – no adjustments were made to link values in order to create desired behavior at the network level. Given that the purpose of this thesis is to demonstrate a methodology, rather than to calibrate the model, choosing link values was seen to be sufficient.

Composing Loops From Individual Links

Of the original five desired attributes for the overall method (Value Links, Loops Composed from Links, Enable Different Flow Types, Valuation Not Dependent on Loop Length, Bound Output Range) I've already satisfied one – valuation of individual links. The following paragraphs describe the decisions I made to compute the strength of loops.

The intent here is to tie high importance links together. The two relevant decisions are:

1. Numerical Range for Links : Several ranges are possible, namely [0,1] or [0,2] or [-1,1]
2. Link Combination Method: Additive or Multiplicative

If using an additive rule, I could have used negative numbers to show detriment and positive for utility. I could then attempt to use information layer to model utility, but this would require a physical layer to convert a stakeholder's utility to a given output (in physical terms). However, I had already decided that I wanted a purely 'Information Layer' approach. Using an additive methodology with only an information layer would cause loops to increase with increasing length, which violates the fourth requirement.

Using a multiplicative rule, the product for a loop can remain bounded if we chose a [0,1] range. This has the associated property that all links less with a value less than 1 will decrease the strength of the overall loop, which again violates our concern that loops valuation should be independent of loop length. Alternatively, I could use a [0,2], with the link valuation distribution centered at 1. This violates the fifth requirement (bounded output), but *may* solve the fourth requirement (valuation independent of loop length), provided link values are evenly distributed about 1.

I chose a Multiplicative rule with the [0,1] range, because I didn't think it was reasonable to enforce any requirements on the distribution of link values. A given set of stakeholders could have only Must Have needs, or only Exciter needs, which would skew the distribution. Additionally, I think that a broader range of loops value would be more difficult to read, because the output cannot be easily interpreted in terms of the link methodology.

For example, the figure below illustrates a typical loop:

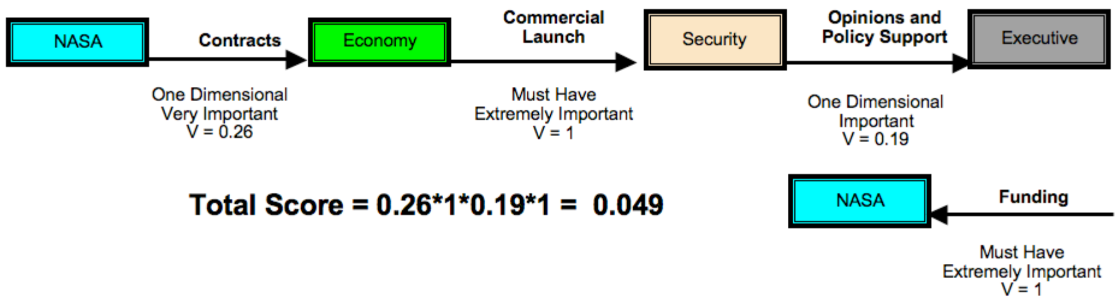


Figure 12 Example of the Multiplicative Rule for Loop Valuation

Given that I've chosen a multiplicative rule on a [0,1] scale, the reader will note that the 'value' decreases through a loop. Rigorously, the 'value' doesn't decrease, because I'm not computing a real quantity. However, is it reasonable that *most* loops values decrease with the addition of a link? There are two perspectives:

1. Each additional link represents an additional stakeholder who must be engaged in the process. If the links are path-dependent (that is to say, stakeholder perceive more than simply the link nearest them), or if there is some over-arching rationale for the loop that stakeholders need to understand in order to use the system, then it could be more difficult to coordinate more actors, all else being equal.

2. Each additional link represents an opportunity to brand NASA involvement in the loop value, or an alternative vehicle by which the loop can be influenced. This view might be favored if we believed links are not path dependent.

Unfortunately, neither of these propositions is properly falsifiable. The utility of the model is dependent on whether the output provides a reasonable and actionable output which is not otherwise logically obvious. If the output stimulates the architect and policymakers to consider new alternatives, then the model has been successful. Ideally, we would construct models under both interpretations, to examine the feasibility of construction and the utility of the output. Due to time constraints, I have elected to focus on the former – in particular, my decision was swayed by the difficulty of capturing 'options' in a policy-space. I feel that the problem of determining the distribution of link values that yields reasonable loop behavior is more tractable under the initial conditions expressed in this thesis.

In order to further examine this problem, it will be essential to determine the correlation between loop length and rank. My hypothesis is that by constraining the feasibility of the shorter loops using internal assets and a reduced set of links, we will still see strong behavior from lengthy loops.

So now we've developed a method for ranking loops, subject to some questions on sensitivity, calibration, and match with intuition. The final piece of the puzzle revolves around causality – how do you we *know* that the input *causes* the output, for a given loop? I discuss this question at the loop level, rather than at the link level, because different loops have different 'rationales' or 'logical flow', which impact how we think about what causation is occurring, on a higher scale than with links. For example, in order to understand why the Security community provides 'Opinions and Policy Support' to the Executive and Congress, we have to look beyond the incoming link, 'Commercial Launch'. Later on, when I discuss the top ranked loops, the reader will note that I give some loops names, according to the 'rationale' behind that loop.

That being said, causation is difficult to evaluate – it is most easily treated by manually sorting through loops to identify poor connections, because there is little we can encode to measure causation. One then has to modify the internal assets in order to eliminate those poor connections.

All that remains is to enumerate all possible loops. Given that the focus is on identifying new loops, and discovering which loops are the most important, I erred on the side of fewer internal assets, to enable more connections. The model was implemented in OPN. Simply stated, at each node, the number of paths through the network branches to cover all possible outputs. When this algorithm is applied recursively to all nodes, the result is that the network explores each feasible path within the network. This belies an important assumption: each individual link has the ability to influence the succeeding stock and output – no two inputs are ever required to be simultaneously present in order to cause an output. In terms of the importance framework, this can be translated as "inputs are independent of each other, weighted only by their Kano-Importance value". A screenshot of the model is given below.

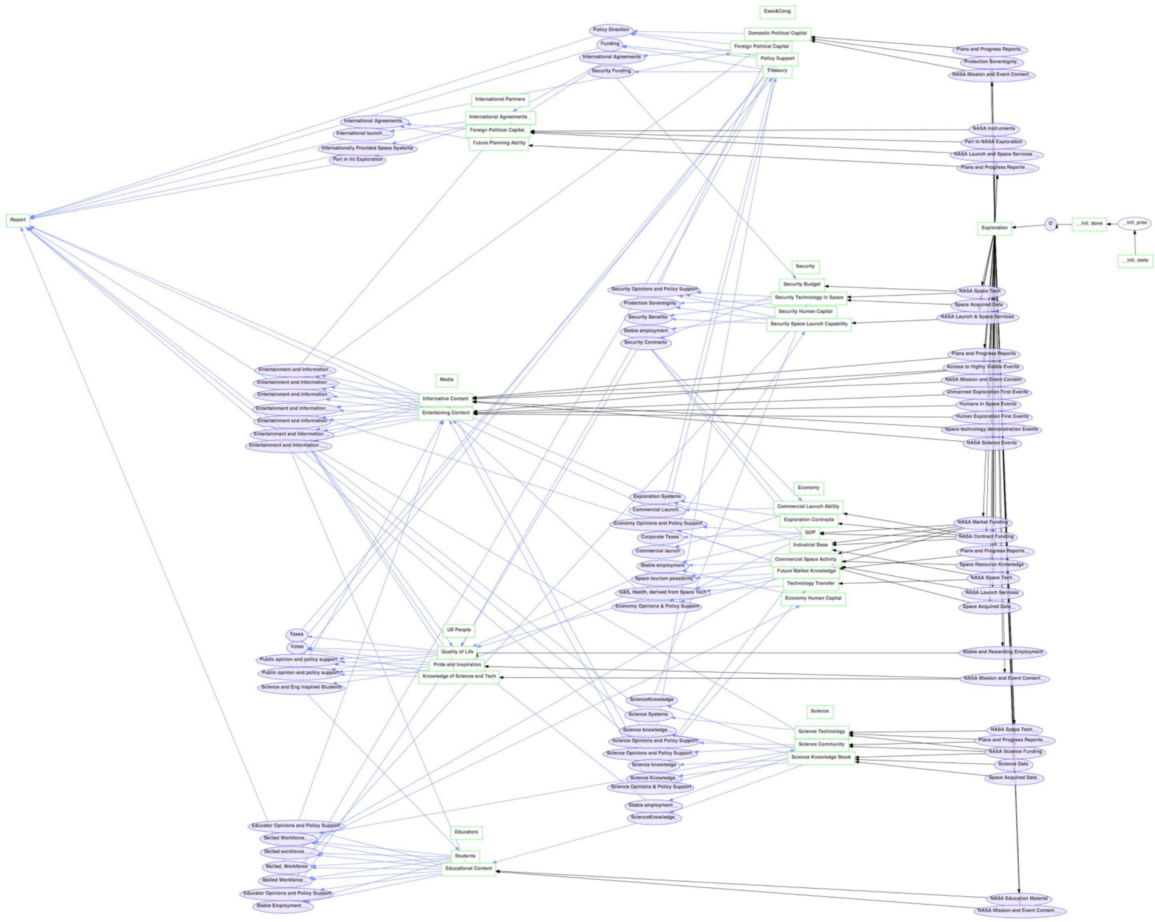


Figure 13 OPN of the Stakeholder Value Model

A full description of the modeling techniques used to create the OPN network can be found in Appendix 2. The only salient concern that merits mention here is that the model is dynamically bounded – at each timestep, a token must meet a minimum accrued partial loop value in order to be propagated forward. This implies that when the model is run, not all possible loops are evaluated, due to limited computational resources. Later, I will investigate whether the loop evaluation scheme is convergent or not – that is to say, whether we can estimate the total weighted average of all loops based on a subset, or whether the addition of new low-value loops will always cause our average to move.

The reader will recall that I had identified 3 types of models for complex systems, namely Multidisciplinary Physical Models, System Dynamics Models, and Network Models. The model I have created is something of a hybrid. It most closely resembles an abstract System Dynamic model, except that stocks and flows are not explicit quantities. However, in terms of the size of space and the search for dominant loops, this model shares some characteristics with conventional Network Models. While I have not yet incorporated any elements from Physical Models, I will show in the next chapter that these can be effectively linked using proximate metrics.

How might these disciplines help inform the computation of loops? Graph theory can be used to show that the number of loops in a strongly directed graph (liker my model) can be bounded by $2^{np}(n-1)!$, where n is the number of stocks and p is the number of flows and auxiliary variables. In practice, this is not a useful bound, as an {n=10, p =10} system already has 10^{35} loops.

There have been some nascent investigations into numerical techniques for identifying the strength of individual loops, using a technique call Loop Eigenvalue Elasticity Analysis (LEEA)[46]. LEEA relies on decomposing a graph into a shortest independent loop set, which is the graph theory terminology for the smallest set of geodetic loops (the shortest path from x to y plus the shortest path from y to x), from which all other loops can be constructed as a linear combination. More rigorously, the Independent Loop Set (ILS) is the smallest set where all of the incidence vectors (which define which edges from a graph are in a cycle) for the independent cycles are linearly independent. Kampmann[47] has shown that the ILS for a graph is equal to:

$$ILS = N - n + 1$$

where: N is the number of arcs
n is the number of nodes

For my model, we have to create a node and two arcs out of each flow in order to translate my terms into graph theory. Therefore, with 80 flows, I have 160 arcs and 109 nodes, for 52 independent loops. Unfortunately, this definition creates the smallest possible loops, which doesn't constrain the loops to begin and end at a particular node.

LEEA then uses the systems' characteristic polynomial (which defines all of the input and output relationships) for the independent loop set to discover the modes of behavior for the system (defined by the eigenvalues of the characteristic polynomial). The key to LEEA is that the strength of the loop is defined as the eigenvalue elasticity:

$$\varepsilon = \frac{d\lambda}{dg}\frac{g}{\lambda}$$

where: λ is the loop eigenvalue
d is the loop gain

This is not directly applicable to my model, in that there is no explicit time behavior (stocks are do not literally accumulate as a result of inputs), and because the model has exogenous inputs. However, there are some useful analogies we can draw. First, it would be interesting to investigate the network to discover the independent loop set, by relaxing the constraint that all loops have to begin and end with a given node. Second, if we consider the loop Kano-Importance value to be the gain, and the NASA output to be analogous to the eigenvalue, we can investigate which outputs have the greatest elasticity.

Should a proper system dynamic model ever be constructed to analyze benefit flow, it would be interesting to conduct a full LEEA. However, as a caution, the user should be wary of the linearization requirements of current LEEA, as well as computational difficulties relating to larger models having to do with repeated eigenvalues.

Having now defined the numerical methodology I will use to evaluate the behavior of the network, the next step is to examine the outputs of the analysis.

4. Loop Results

This chapter has several goals:

1. Define what types of results can be drawn from the existing model
2. Examine the results against sanity checks
3. Analyze the results to determine what can be learned
4. Answer the concerns raised earlier, namely
    a. Does my numerical scale create realistic equivalencies between different loops?
    b. Does loop length correlate with rank?
    c. Fundamentally, does stringing together strong links create strong loops?
5. Extrapolate the results to answer the question some of the value questions beyond the scope of the model

All data presented in this section is derived from Kano-Importance data created by the author. The data is intended to be representative of the opinions of the individual stakeholders considered, and some calibration analysis is provided below, but biases will necessarily be present. As such, the focus is to demonstrate the methodology using reasonable values. Should the methodology and results appear useful, real data would need to be collected.

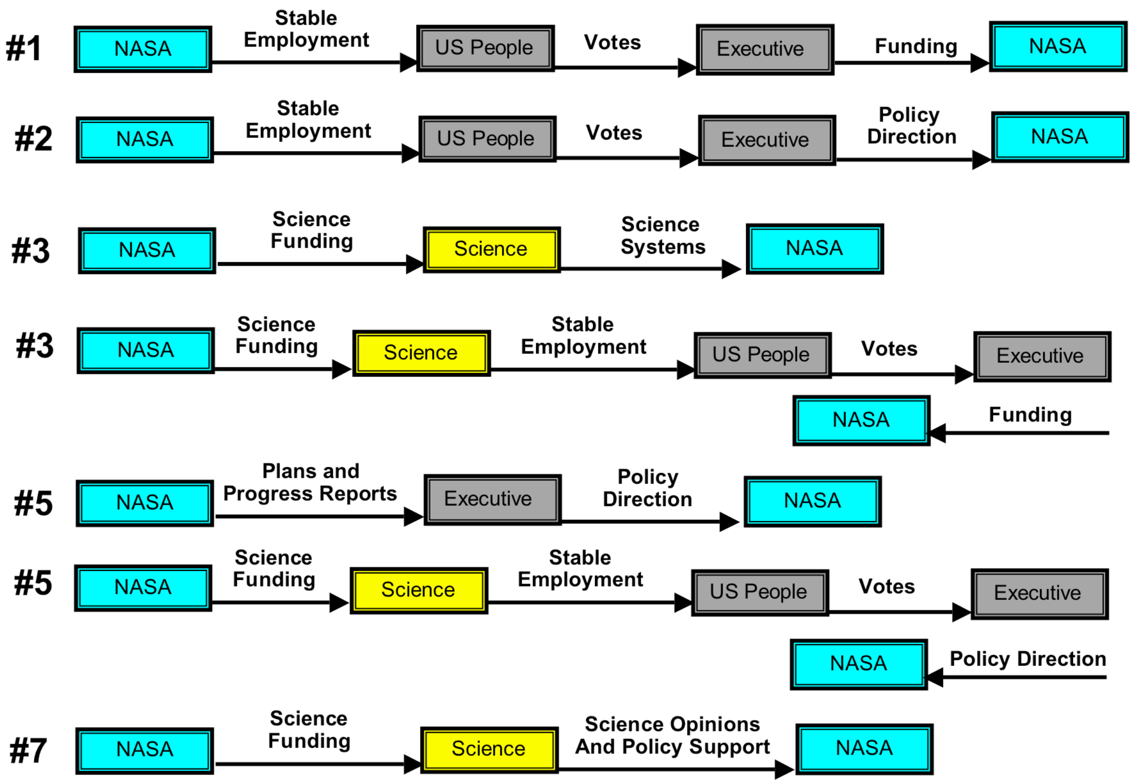
4.1. Model Outputs

The model outputs shown in the section below were drawn from a sample of 252 loops, created using a bound of $V > 0.01$ on each link.

4.1.1. Ranked loops

The top seven loops are shown graphically below.

Figure 14 Top 7 Value Loops



From this most basic view, we can already note a couple of things. First, not all stakeholders are represented in the most important loops – in fact, only half are present. Second, the model enumerates loops that differ only by one link. Third, there are a dominant set of NASA outputs and inputs that appear in many loops.

Looking now at a larger fraction of the data, the top 30 loops are shown below, with only the flows indicated.

Table 5 Top 30 Value Loops

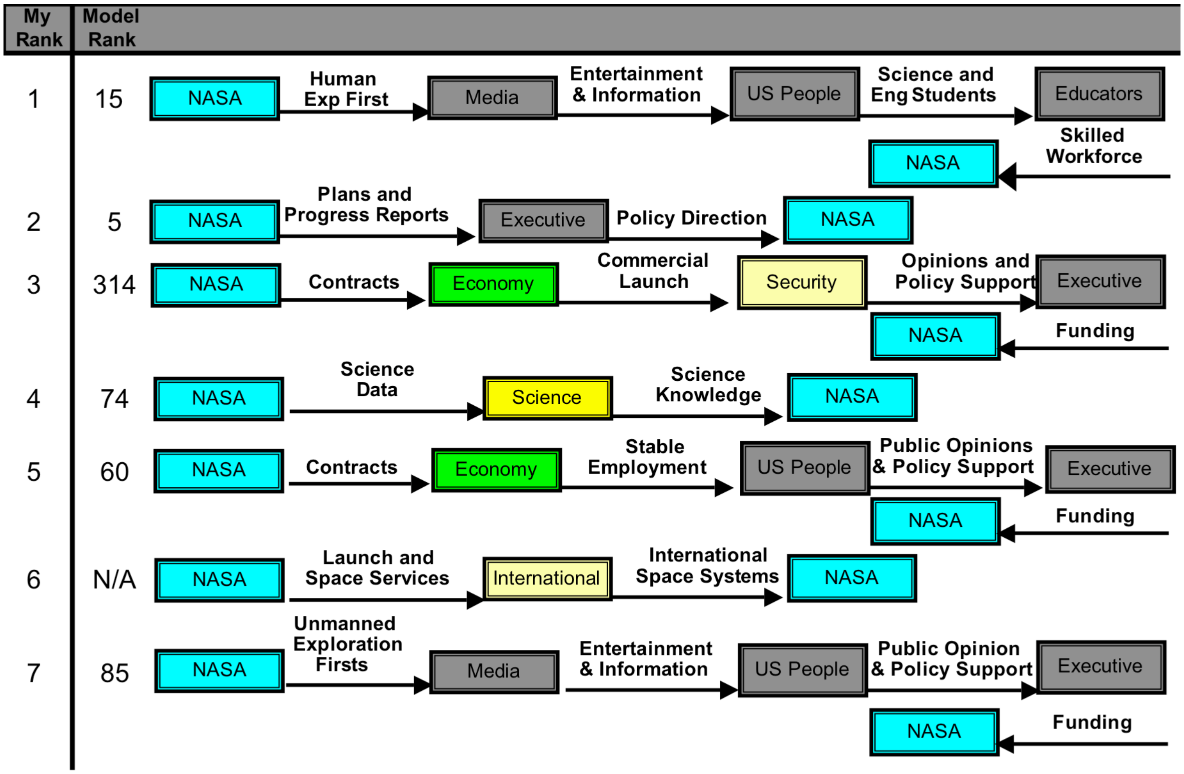
Rank	Score	Path
1	0.780	Stable and Rewarding Employment + Votes + funding
2	0.608	Stable and Rewarding Employment + Votes + Policy direction
3	0.550	NASA Science Funding + stable employment + Votes + funding
3	0.550	NASA Science Funding + Science systems
5	0.429	NASA Science Funding + stable employment + Votes + Policy direction
5	0.429	Plans and Progress Reports + Policy direction
7	0.330	NASA Science Funding+ Science Opinions and policy support
8	0.257	NASA Contract Funding + Commercial launch + Security Benefits

		+ Votes + funding
8	0.257	Human Exploration Firsts + Entertainment and Information + Votes + funding
8	0.257	NASA Contract Funding + stable employment + Votes + funding
8	0.257	Space Acquired Data + Security Benefits + Votes + funding
8	0.257	Human Exploration Firsts + Entertainment and Information
8	0.257	NASA Contract Funding + Commercial launch
8	0.257	NASA Contract Funding + Exploration Systems
15	0.201	NASA Science Funding + Science Knowledge + skilled workforce + Stable Employment+ Votes + funding
15	0.201	NASA Science Funding + Science Knowledge + Skilled workforce + stable employment + Votes + Policy direction
15	0.201	Science Data + Science Knowledge + skilled workforce + Stable Employment + Votes + funding
15	0.201	NASA Contract Funding + Commercial launch + Security Benefits + Votes + Policy direction
15	0.201	Human Exploration Firsts + Entertainment and Information + Science and Eng Inspired Students + Skilled workforce
15	0.201	Human Exploration Firsts + Entertainment and Information + Votes + Policy direction
15	0.201	NASA Contract Funding + stable employment + Votes + Policy direction
15	0.201	Space Acquired Data + Security Benefits + Votes + Policy direction
15	0.201	Unmanned Exploration Firsts + Entertainment and Information + Votes + funding
15	0.201	Human Exploration Firsts + Entertainment and Information + Policy direction
15	0.201	NASA Science Funding + Science Knowledge + Skilled workforce
15	0.201	Science Data+ Science Knowledge + Skilled workforce
15	0.201	Stable and Rewarding Employment + Public opinion and policy support + funding
15	0.201	Unmanned Exploration Firsts + Entertainment and Information
29	0.182	NASA Market Funding + stable employment + Votes + funding
29	0.182	Space Acquired Data + stable employment)+ Votes + funding

Notice that there are number of ties (13 loops at #15), despite the fact that the loops are 4 and 5 links long. This suggests that feasibility has eliminated a number of the short loops, in that the full space of value permutations are not represented. For example, for loops with {length = 2, value > 0.2}, there are 19 possible combinations, only 6 of which are represented in this model.

Recognizing that it is easier to rationalize the output by observing it, I composed a separate list of what I thought were the top 7 loops. It is interesting to see how my choices diverged from the model outcomes.

Figure 15 Comparison of Expected vs. Realized Top Loops



There are a couple of factors at work here:

1. I picked a greater distribution of stakeholders and links. Part of this is that the model will enumerate similar links, whereas a person wouldn't typically do so.

2. My links were on average longer than those in the model (3.25 vs. 2.75) for the Top 8. However, if I had chosen my top 50 loops, I would also have expected to see my group more narrowly distributed about 3 or 4 than the model – a result of the increased difficulty of conceptualizing longer loops.

3. It was more natural for me to focus on benefit rather than regret. Essentially, I didn't weight regret highly, which explains why jobs are not placed highly.

4. My Loop 3 is typically given as justification's for NASA's spending, but neither ranks significantly in the model. The model is suggesting that NASA's ability to influence the relevant stakeholders here is lower – this does not pass judgment on the probability of the event happening. Rather, the model functions on conditional probability: "If you had this benefit, how would it impact you?". We would therefore expect powerful but low probability mechanisms to be over-represented in the model results. This,

however, argues in favor of the discrepancy here. The real answer for Loop 3 relies on the competition aspect – there are a number of other sectors that stimulate commercial launch.

5. My Loop #6 is not a feasible loop in the model. There is a specific modeling decision responsible for this – I required international agreements be transacted at the Executive level, whereas actual goods and services are transacted directly by NASA. This suggests that NASA cannot directly influence the number of international space systems it receives – it has to take indirect routes through the Executive. This philosophy is certainly endorsed by Administrator Griffin, who has suggested a number of times that NASA's goals are set externally. However, encoding this in the model ignores the facilitative discussions, operational realities, and architectural attributes that all have an impact on international collaboration. Significant post-analysis will be required in order to evaluate whether this was an appropriate modeling decision, provided in Section 5.3 Architecting in the Real World.

Given the loops that many of the loops represented in the Top 50 stem from the disbursement of money by NASA, rather than the benefit associated with *what* that money was spent on, I compiled a list of the top Non-Welfare loops. Specifically, I eliminated loops that begin with NASA providing money and loops that generate employment. The results are shown in the table below.

Table 6 Percentage of Non-Welfare Loops

Loops	% Non-Welfare
Top 50	38%
Top 100	43%
Top 200	45%

Interestingly, the percentage welfare seems to be decreasing slightly as we take progressively broader sets of loops. Despite the fact that money links are a minority in the model, in many cases they represent the most desired inputs, which biases their loops towards the top section of the loop rankings.

The distribution of rankings is shown in the figure below. It is apparent that this is a relatively steep curve, as I noted earlier – feasibility constrains many of the permutations which would contribute to a more gradual slope. There are roughly 60 loops that have a loop value greater than 0.1 – this is equivalent to a strong loop with a single weakest link equal to 0.1, of which 2/3 of the Kano-Importance combinations are greater. There is a trade-off here, between a desire to rank loops more evenly to allow for error in the modeling assumptions, and a desire to have that the tail of the curve converges to zero reasonably fast, so that we can bound the solutions without enumerating *all* loops. This will be investigated more thoroughly in the sensitivity analysis to the Kano Multiplier.

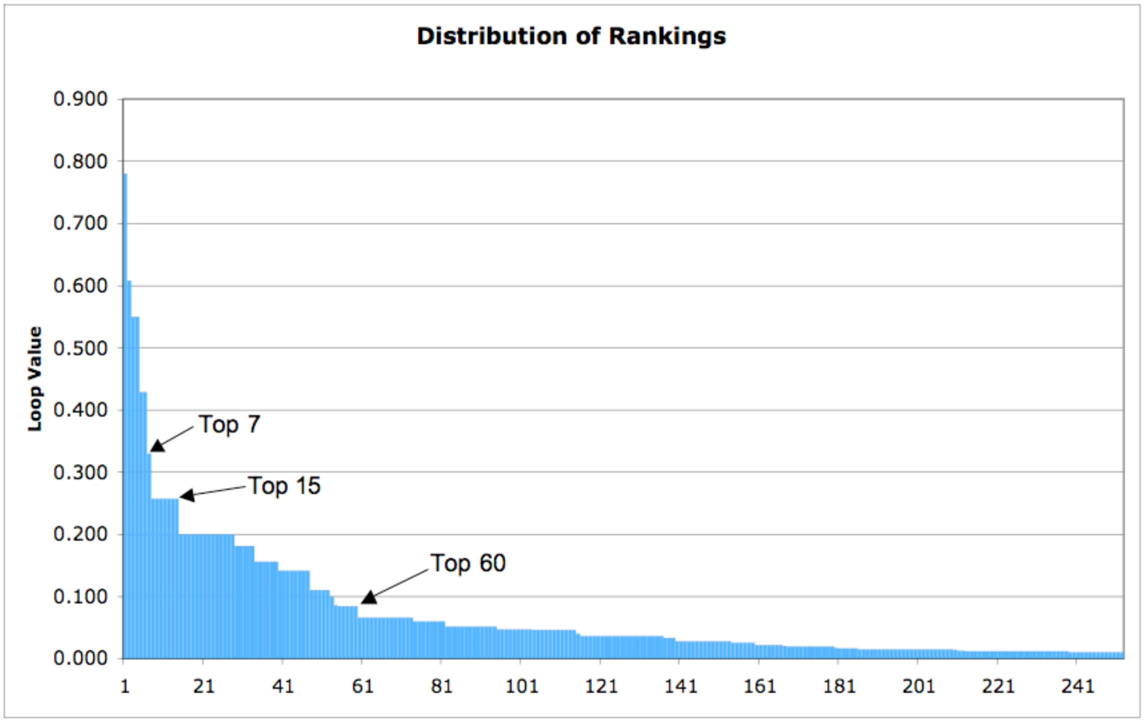


Figure 16 Distribution of Loop Rankings

4.1.2. Stakeholder Importance

The charts below represents the most direct output of the analysis, a determination of which stakeholders are most important. However, I will argue that this is not in fact the most useful product of the analysis, essentially because it is difficult to make decisions based on a ranking of stakeholders.

To determine the 'importance' of stakeholders, I used a weighted sum of the stakeholder's participation in important loops, called the Stakeholder Loop Occurrence (SLO). For each time that a stakeholder participates in a loop, the score for that loop is added to the stakeholder's total. The final values are normalized by the sum of the scores for the loop set considered.

$$SLO(s) = \frac{\sum_{i \varepsilon S} r_i}{\sum_{\forall i} r_i}$$

where: r = rank of loop
s = the set of all loops that contain the stakeholder
i = loop index

This necessarily places all stakeholders at an equal participation rate within the loop. The alternative would have been to weight the stakeholder's participation in the loop by their input score (assuming a benefit pull), or the score of the stakeholder who receives their output (assuming a benefit push). However, this would double count the stakeholder's contribution to the loop, as their link value has already been factored into the loop score.

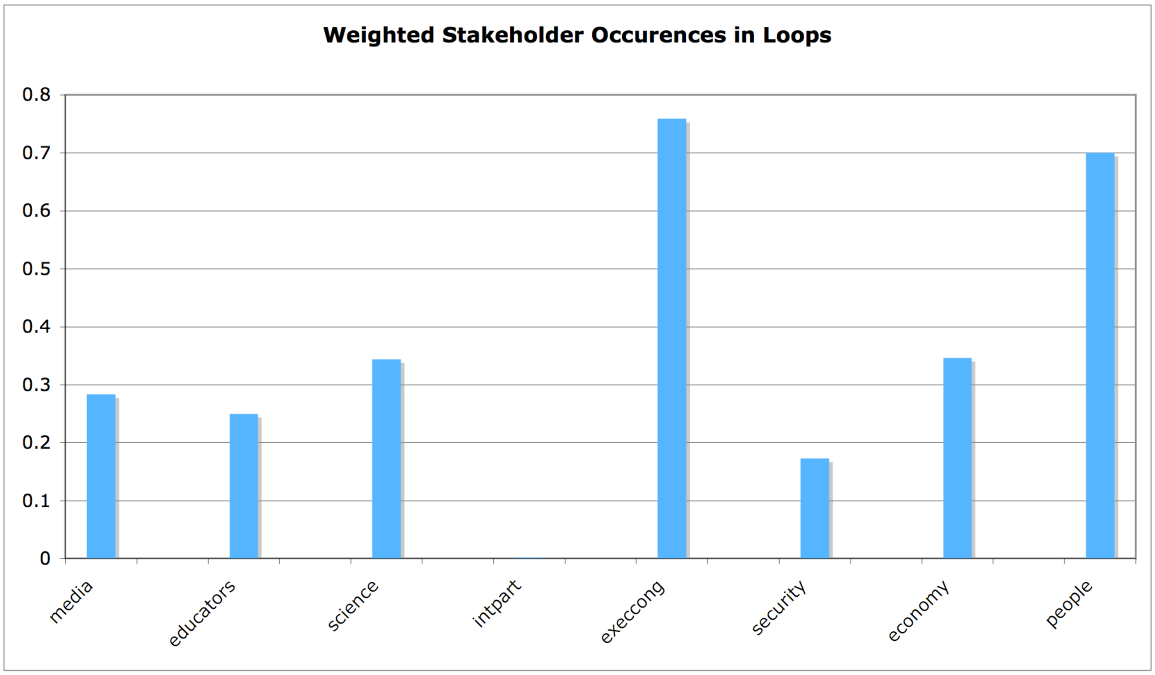


Figure 17 Weighted Stakeholder Occurrences in Loops

There are at least 3 regimes shown here. Clearly, the Executive and the US People participate in many more important loops than do the remaining stakeholders. Science and the Economy play the next most important roles, followed closely by the Media and Educators. Lagging well behind, we can see that the Security community, and in a small but non-zero capacity we see the International Partners.

Notice that the loop model produces a very different output than if we were to value stakeholders by their direct inputs to NASA, as shown in the graph below. This graph represents what a myopic, reactionary view of stakeholders would look like. Note the strong emphasis on the economy, the non-existence of Security and US People stakeholders, and the resurgence of International Partners.

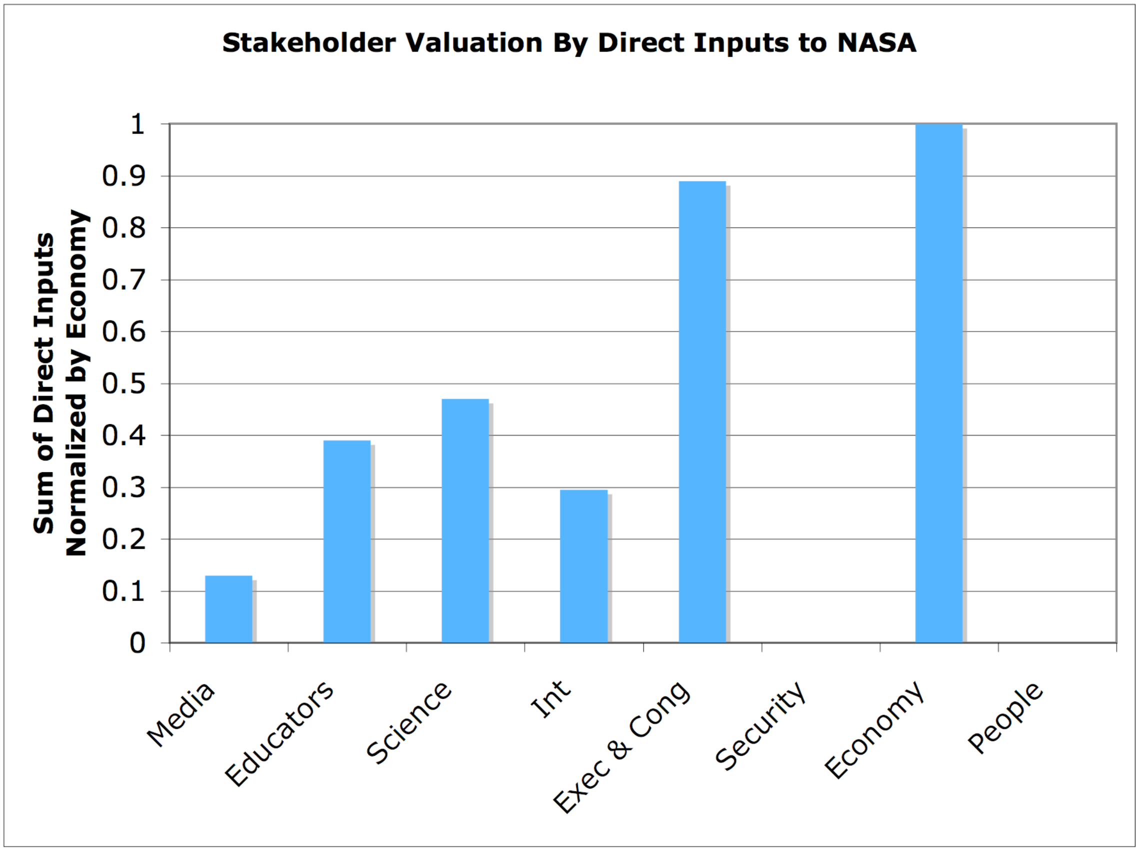


Figure 18 Stakeholder Valuation by Direct Inputs to NASA

In the following discussions, I discuss how these stakeholder weightings compared with existing data.

How does NASA view its stakeholders?

A recent internal study[48] (Dec. 29, 2006) by the NASA Communications Office provides an informal view of the perceptions of NASA employees as to the relative importance of different audiences for NASA. Note that the use of the word 'audience' can be interpreted differently from 'stakeholder', but for this coarse analysis Iwill consider them equivalent. The study cannot be verified as original, as it was leaked on NASAwatch.com website – however, a nearly identical 'Validation Session' copy was officially released by NASA on November 6, 2006.

The survey was conducted on October 11-13, 2006, using 80 NASA employees, with a 50/50 split between Headquarters and Center personnel, and with each center represented. The chief bias concern here is that communications personnel dominated the sample, although there were representatives from all directorates included. This might suggest a bias towards 'traditional' stakeholders, the US Public and the Executive. The data from the survey is shown below.

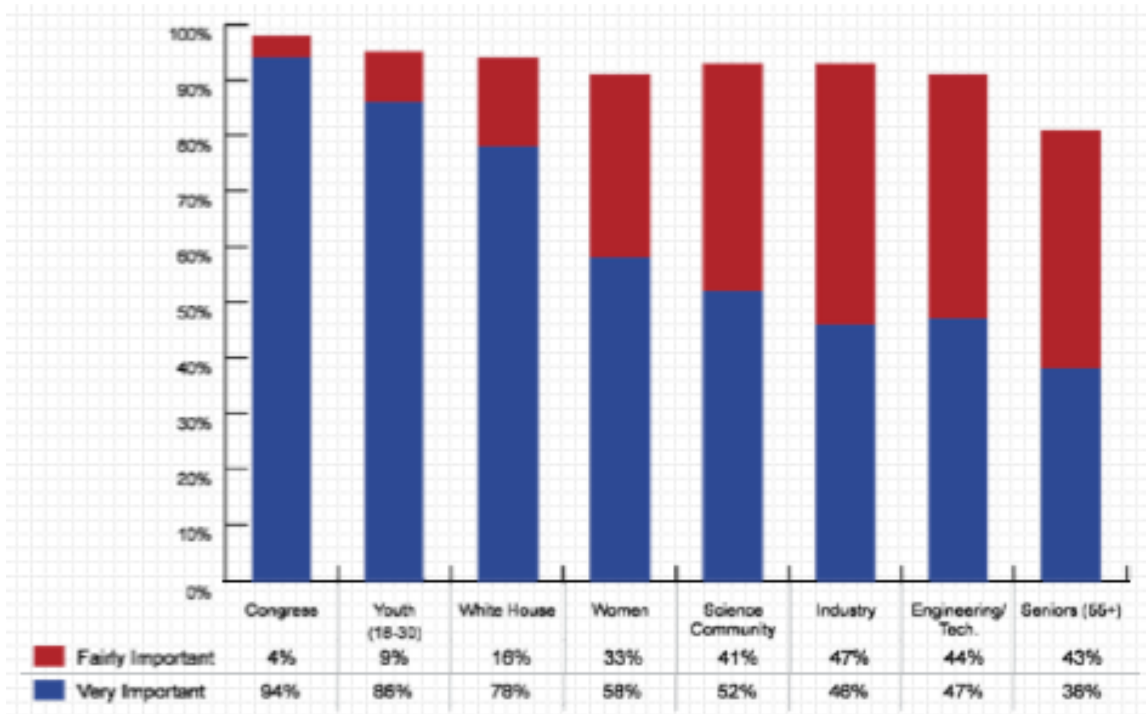


Figure 19 NASA Communications Office Study of NASA Stakeholder Perceptions

Using some rough analysis, I converted the NASA survey data to equivalent terms in terms of my importance scale. Specifically, I equated NASA's "Very Important" with my "Extremely Important", and NASA's "Fairly Important" with my "Important", and assumed that the remainder (not all columns sum to 100% in the diagram above) was equivalent to my "Not At All Important". Using these values, I converted the four stakeholders represented to my importance scale, equating Industry with **Economy**, Science Community with **Science**, averaging White House and Congress to create the **Executive and Congress**. For the **US People**, I used the relative percentages of the population[49] to scale Youth, Women, and Seniors, assuming that the remainder of the population corresponds to the average of the 3. These assumptions should be taken as crude at best, but they do allow us to make a relative comparison of the stakeholders.

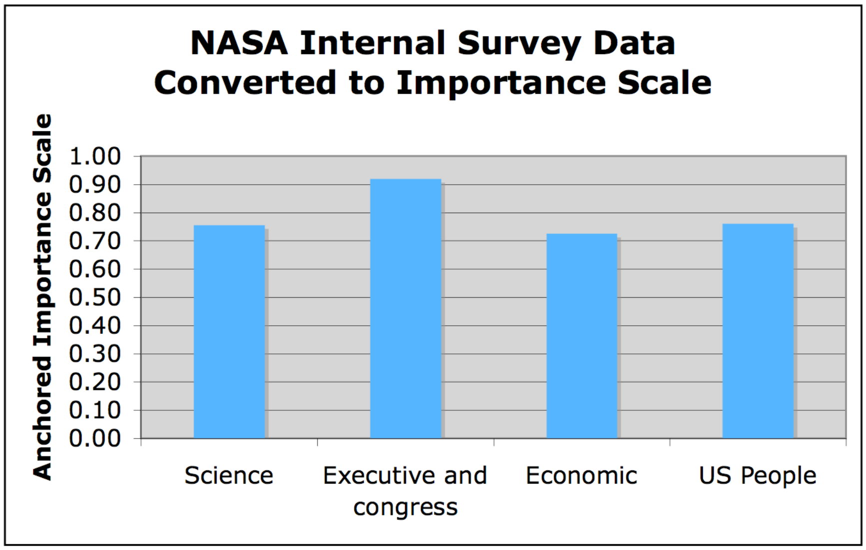


Figure 20 NASA Internal Survey Data Converted To Importance Scale

We can see that there is less differentiation between stakeholders in this data than in the model output. While the Executive and US People still come out on top, we can see that the relative importance of Science and Economic stakeholders is much higher. What is most interesting about the data is the broad differences in importance scores of the different categories of US People. For example, Youth 18-30, who represent only 9% percent of the population, are much higher ranked than other segments.

Shifting our focus to recently published NASA studies, what can we glean about the prioritization of stakeholders from the relative priorities of goals? The deputy administrator held a press conference on the Exploration Strategy and Architecture in December of 2006, defining six 'themes' for lunar exploration:

- Human Civilization (US People)
- Scientific Knowledge (Science)
- Exploration Preparation (NASA / US People)
- Global Partnerships (International Partners)
- Economic Expansion (Economy)
- Public Engagement (Educators / US People)

I have asserted the corresponding stakeholders from my model in brackets above. Note that the Security community is not noted as a stakeholder, nor is the Media (although Public Engagement could be construed to include the Media). Unfortunately, the list of chosen objectives corresponding to these themes was not published, so we cannot infer which themes are most strongly backed by requirements. The largest discontinuity between my model and the NASA presentation is clearly the presence of International Partners. While there is a clear desire to include International Partners, current NASA policy suggests that they should not be placed on the critical path, particularly with respect to transportation capabilities. This is in keeping with the valuation of International Partners in the model, which asserts that the benefit would potentially be great, but that there is a desire not to have regret associated with placing International Partners on the critical path, should there be delays. I'm not asserting that this is the correct policy, but simply that pains were taken to make the model data reflect current policy.

How Does the Executive View NASA's Stakeholders?

Documents from the Executive don't enable us to get a better sense of a prioritization of stakeholders. As noted in Section 3.1 *Rebuilding the Model for Consistency*, the Vision for Space Exploration defines five main stakeholders (including security!), but doesn't provide a prioritization. Recognizing that there could be negative consequences for the Executive of defining numerical rankings of stakeholders, this was to be expected.

How Do the US People View NASA's Stakeholders?

The best source of data on NASA's perceived stakeholder context comes from public surveys, where there are no consequences to individual respondents to asserting priorities. Several data points exist:

The Harmonic study[50] asked "Who is NASA for?". This is analogous to asking "What is the one thing NASA should do?", but should at least give an idea of what the public thinks is NASA's single-most important stakeholder. No sample size was given in the data.

- 60% the public, of which 30% said exclusively the American public
- 18% the government
- 15% scientists
- Remaining 5% not shown in survey

It is interesting that this survey also ranks the government above scientists, as my model does. Additionally, the fact that the Economy is completely non-existent in this case is quite surprising!

The Gallup poll (in the Strategic Communications study) asked a slightly different question: "What do you think is the main reason NASA continues to explore?".

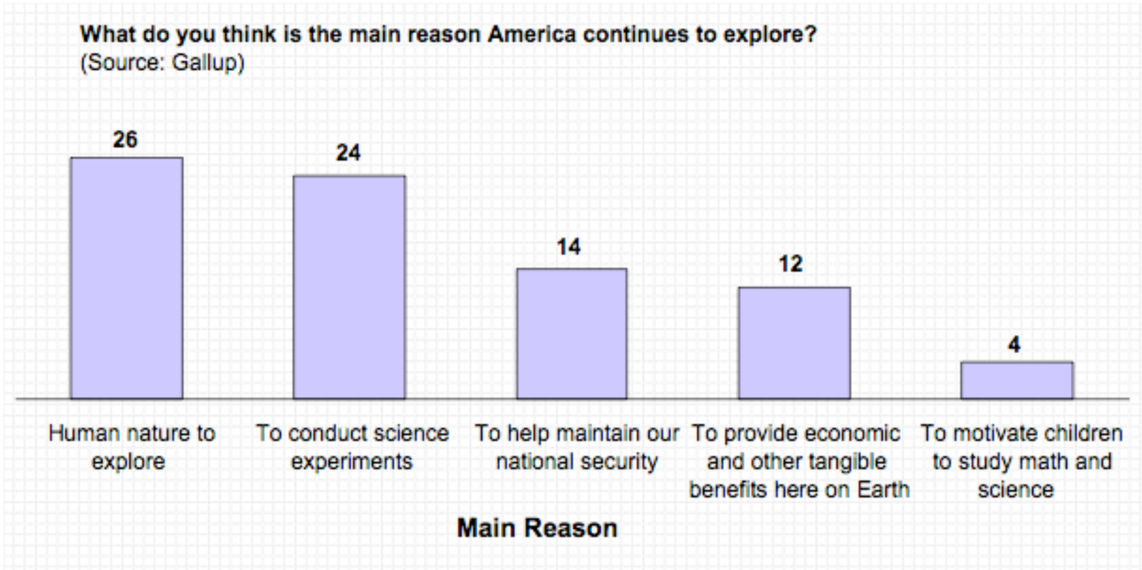


Figure 21 Gallup Poll Data on Motivation for US Exploration

The analogy from my model is to examine all the value chains that start at NASA and end in the US People. Using a bounding threshold of V>0.01, I examined all chains that end in the analogous value flow. Given that my model doesn't differentiate between the exploration producing entertainment and exploration producing inspiration (until we see the output of the US People), my results are the equivalent of lumping 'Human nature to explore' with 'To motivate children to study math and science'.

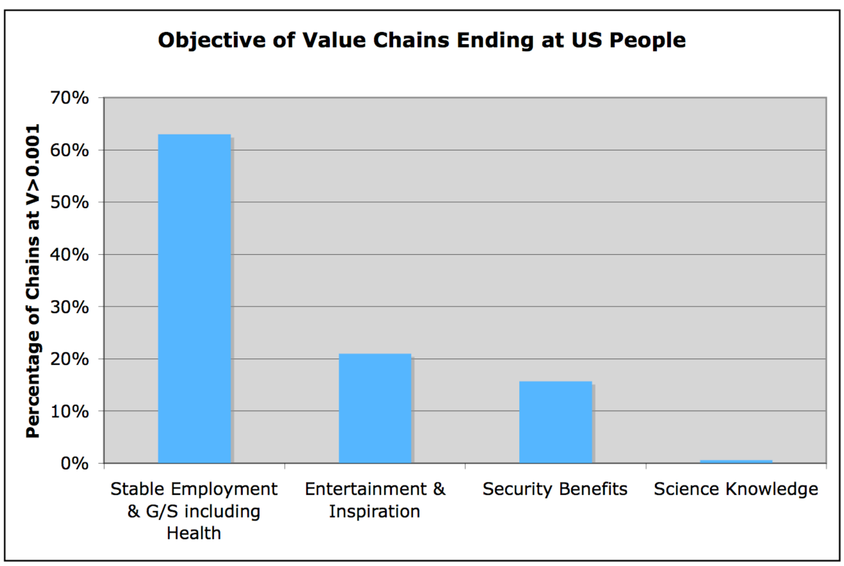


Figure 22 Objective of Value Chains Ending at US People

We can see that my model predicts roughly the same Entertainment & Inspiration and Security Benefits, but then undervalues Science and overvalues Economic Benefits. Science is undervalued because the US People don't directly benefit from Science

Experiments in my model, they benefit from entertainment from science knowledge, and they enjoy indirect economic benefits from that science knowledge. As such, part of the Science benefit is caught in the Economic benefit, and another component is caught in Security benefit. The overvaluation of Economic Benefit is partially due to my benefit accounting (as described above), but more significantly, because of my weighting on detriment, which values the jobs from NASA much higher than a survey respondent ever would. It is worth noting though that there is a distortion between asking for 'the most important output' vs. allocating a fixed budget to several activities.

There are clearly large discrepancies between how different groups view NASA's Science mission. Within NASA's, 75% of the civil servant respondents highlighted "Advances Knowledge" or "Enhances Scientific Discovery" as NASA's top priority. From the Public's perspective, Science's share of the top priority spot varies from 15% to 24% (as shown above, variation based on how you ask the question). My valuation is much closer to Public's than to the NASA numbers, and I would go so far as to suggest that NASA's actions don't necessarily reflect the high numbers from the poll, even from a basic budgetary standpoint.

Principle
Computation on value flows can discover discrepancies between how different groups perceive the mission of the organization

The difficulty with these questions is first, how does one realistically use this type of stakeholder information? In order to better answer this question, I re-examined the stakeholder question in a different light.

4.1.3. Reciprocal Stakeholder Power Analysis

Further thought on the issue of stakeholder valuation led me to the idea that the relative balance of power between stakeholders is one of the key piece of information that a decision maker uses. Therefore, the question becomes "*How do these feedback loops inform the balance of power between stakeholders and the organization?"*.

I postulate that there are a number dimensions of stakeholder power:

1. Importance of the resource
2. The availability of alternative sources (buyer and supplier power)
3. Formalized reporting relationships (legal power)
4. Each stakeholder's ability to modulate their outputs (threat capability)

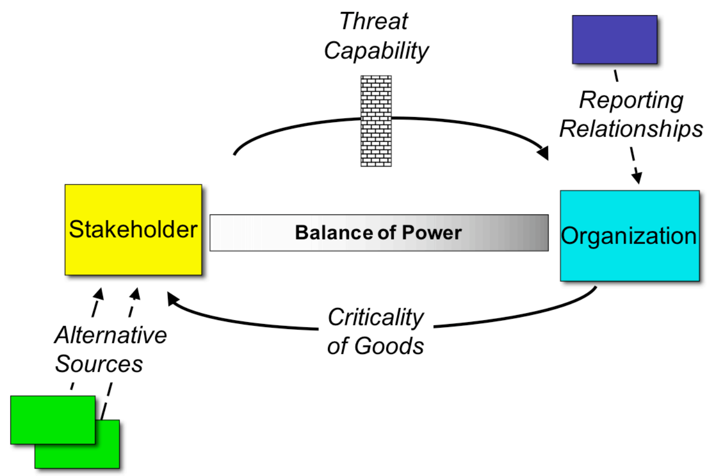


Figure 23 Dimensions of Power Between Two Actors

We can examine the importance dimension using our existing framework of stakeholder value loops. We can compute an approximation of the importance of the benefit that flows between NASA and each of its stakeholders. Each of the graphs below defines the sum of benefit chains that are provided to each stakeholder, and the sum of the chains that pass from that stakeholder back to NASA.

This analysis is shown with three different filters. First, I examine only the direct transactions between NASA and a stakeholder. Previous analysis indicates these are in the minority, composing just 8% of the important value loops. Second, I show the direct transactions plus the top 5 Indirect chains (ranked using the Kano-Importance methodology) between NASA and a stakeholder. I define an indirect chain as any set of links that passes through at least 1 other stakeholder. My results show indirect chains with as many 6 links occurring. Third, I capture all chains with a value greater than 0.01 which captures as many as 100 value chains in each direction.

The horizontal axis represents the sum of the value chains, with the numbers inverted in the 'From Stakeholder' case for plotting. The exact numerical value is less important – the numerical framework I employ is intended for making relative comparisons.

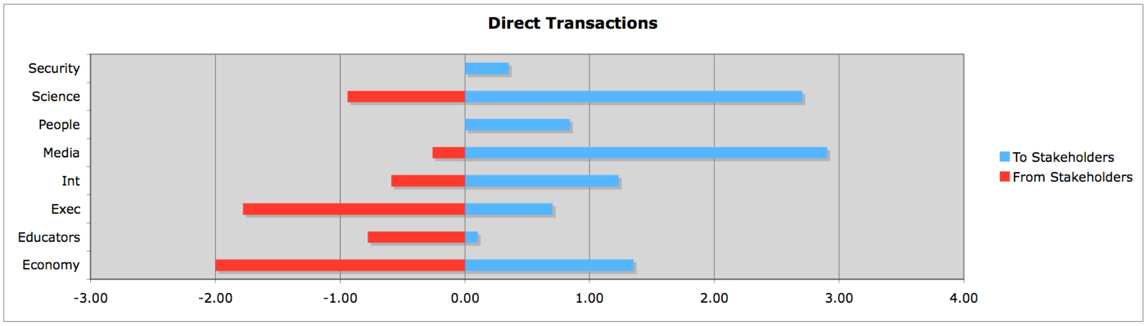


Figure 24 Power Balance For Direct Transactions

We can see that there is a net bias in direct transactions towards stakeholders. That is to say, NASA is a net contributor to its environment, or in other terms, NASA's stakeholders, on average, have more power over the relationship. It is also interesting that NASA receives nothing directly from Security or the US People.

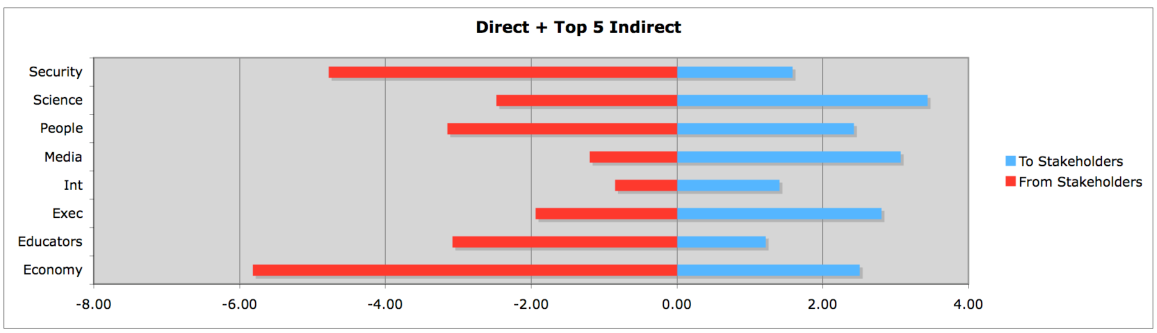


Figure 25 Figure 25 Power Balance With Top 5 Indirect Chains

If I now include the Top 5 Indirect transactions, the balance shifts – NASA values what it receives from stakeholders more than they value NASA's output. Notably, NASA values highly what Security provides, but doesn't have much leverage over Security. The balance of power with the Executive and Congress has also shifted *in favor* of NASA.

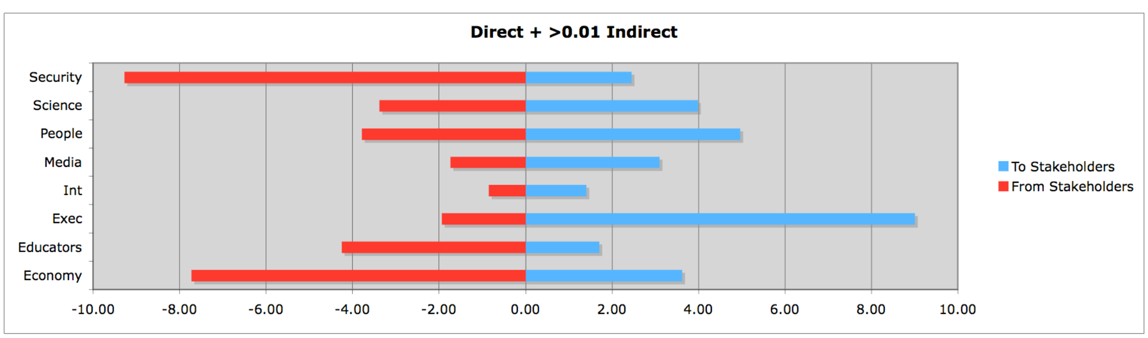


Figure 26 Power Balance With V>0.01 Indirect Chains

Looking at a broad view of the balance of importance (the above figure), we can see that the average balance is close to neutral, but individual relationships vary significantly. For example, NASA provides more to International Partners than it values the return, and NASA receives more benefit from Educators than it can possibly influence.

We can also note some unusual outputs – for example, one would predict from this model alone that NASA exerts power over the Executive. As I have not included legal power (by which the Congress exercises monitoring authority over NASA), or the relative ease with which outputs can be modulated to threaten the receiver (where the Executive and Congress have significantly more latitude), I do not capture the important dimensions of this relationship. In this sense, direct only links were a better predictor of the balance of power.

The relative balance of power with stakeholders should inform how the architect thinks about the prioritization of requirements within the architecture. In an organic architecting process, I assert that concerns of important stakeholders will be satisfied first, in order to avoid having that stakeholder exercise their power. This essentially amounts to minimizing the organization's regret. The remaining design space is left to optimize the benefit to the remaining stakeholders.

Reciprocal Stakeholder Power Analysis With Competition

Having conducted the first order analysis with only importance balances, we can ask what else would be required in order to add competition? The reader will recall that I identified importance and competition as the two most significant concerns to model from the perspective of the agent problem. Additionally, competition was the second factor identified in understanding reciprocal stakeholder agreements.

I focus only the outputs of the stakeholder for which the stakeholder has a monopoly, but then excepting those chains where the input to the receiver is a monopsony. Alternatively, I could attempt to bias the individual link values up or down based on the level of competition – however, it would be difficult to measure the premium that is extracted across different goods and services.

For a first pass, I examine only the monopolistic (1 vendor) and oligopolic (2 vendors) markets, less the monopsonistic markets (1 buyer). For the oligopolistic markets, I halved the transaction value, to recognize that an oligopoly has less bargaining power than a monopoly. Again, I use 4 filters: Direct, Top 5, Top 10, and Top 0.1. If there are not enough monopolies to fill the top 5 or 10 with only monopolies, I fill the remainder with the oligopolies at half value.

To determine which flows represented monopolies, I required that monopolies have the ability to band together to withhold the output. For example, scientists cannot form monopolies, because they are too distributed. However, the Air Force can form a monopoly.

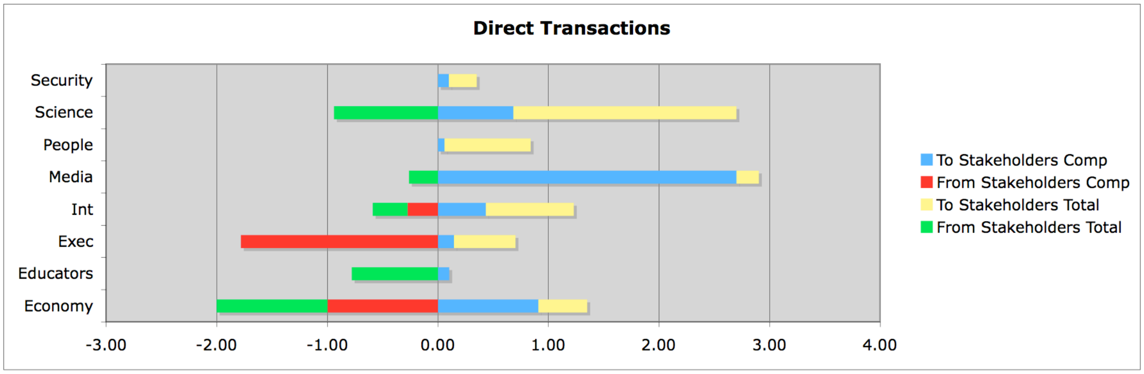


Figure 27 Power Balance With Competition Filter for Direct Transactions

The above figure shows the output of this analysis. Specifically, the blue and red bars, marked 'Comp' for Non-Competed, show the uncompleted balance of power. The Yellow and Green bars then layer on the other ½ of the value from oligopolistic flows, as well as the other competed flows.

The competition filter has eliminated a number possible benefit chains. Note that NASA has a one way relationship with 5 of its stakeholders when competed flows are eliminated. Note also that the Executive has no direct flows to NASA that aren't monopolies, as we would expect. The only stakeholder that sees a significant balance of power change through the competition filter is International Partners, which moves from being neutral to a NASA advantage.

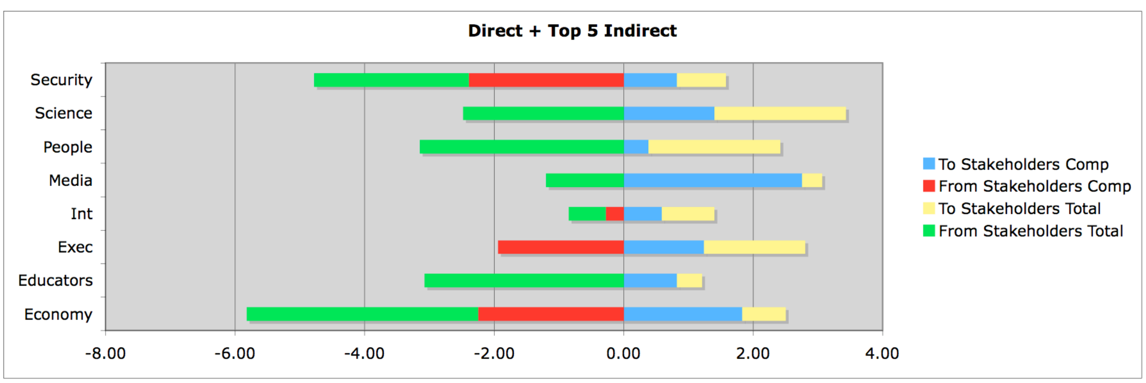


Figure 28 Power Balance With Competition Filter Including Top 5 Indirect Chains

In the Top 5 Indirect flows, we can see that NASA offers monopolistic flows to each stakeholder. While NASA is certainly unique, this could also be an artifact of the level of detail chosen for NASA (17,000 employees vs. several orders of magnitude more for each of the Economy, the US People, International Partners, and Science). We can also see that the Educators provide a lot of competed goods (essentially, one university could never hold buyer power over an industrial group), as do Science and US People.

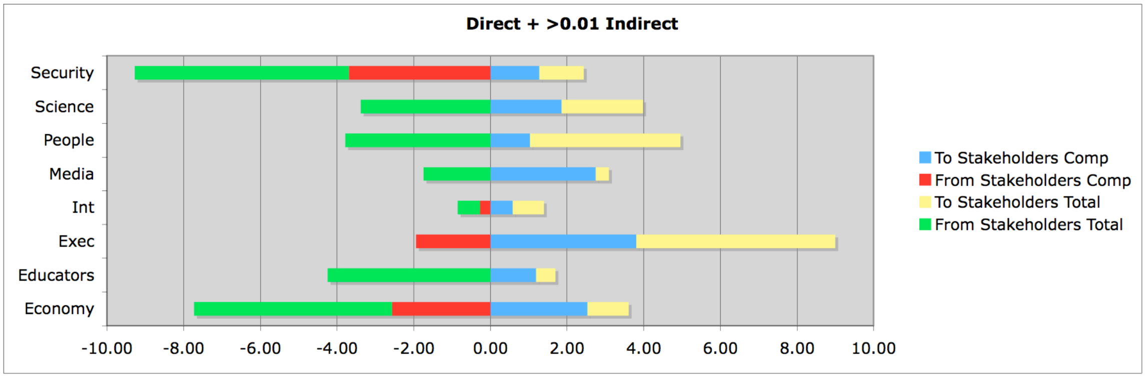


Figure 29 Power Balance With Competition Filter Including V>0.01 Chains

Choosing a larger set of the data, many of the relationships remain stable with respect to the previous level of detail. However, we can see a significant amount of competed flows to the Executive bolstering NASA's power (which is in turn limited by the legal constraints and reporting relationships).

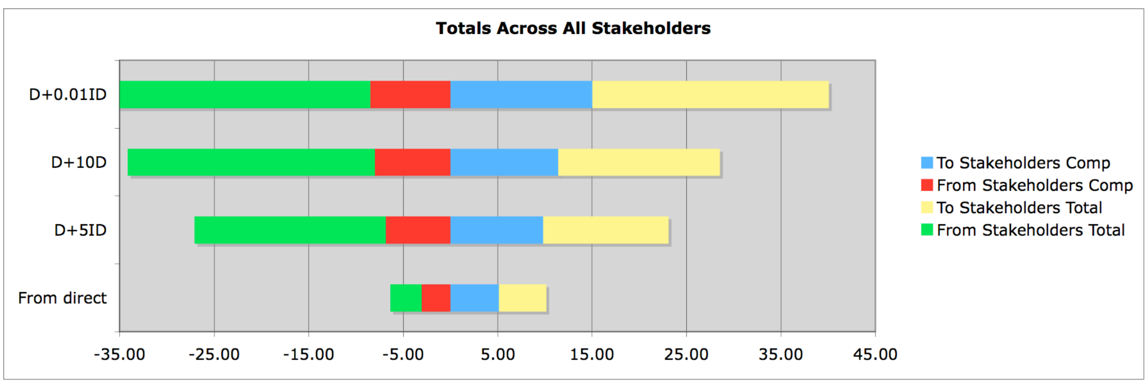


Figure 30 Power Balance Aggregated Across All Stakeholders

Finally, looking at the balance of competed and non-competed flows, we can see that NASA's outflows are more likely to be monopolies than are those of its stakeholders. Considering only monopolies and oligopolies, NASA is a net contributor, as compared with an neutral or even stakeholder- heavy importance balance when all flows are included.

Having answered the question of competition for NASA's outflows, the real question becomes "Can NASA really extract monopolistic pricing?". I believe the answer is No for the majority of outputs, in part because of legal constraints and stakeholder complaint loops. Furthermore, NASA is not a provider of essential services (with the exception of jobs and some types of funding), which suggests that NASA's threat would be a hollow one, if not a contested one. This reinforces our decision to focus on positive feedback loops in creating the model.

Note that I've only represented the first onion layer on competition, in the sense that all of the links in the value chain between NASA and the stakeholder face possible competition – as shown graphically in the figure below.

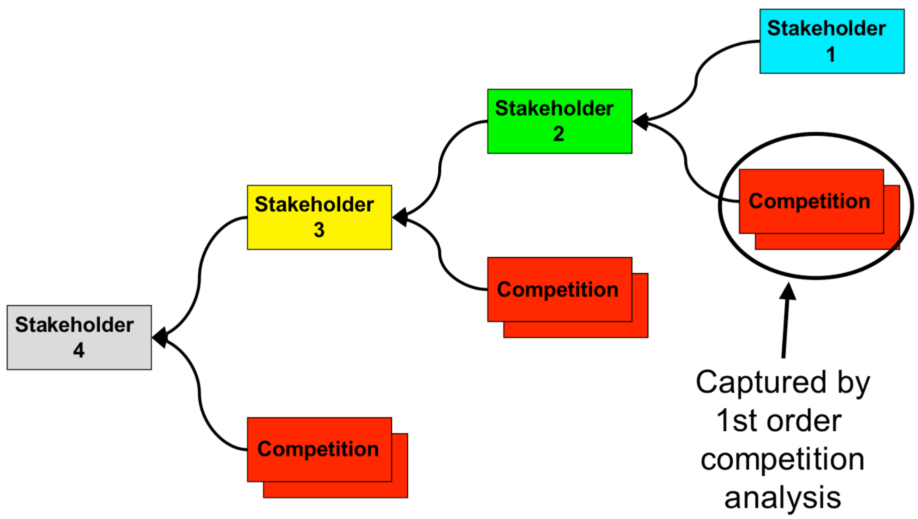


Figure 31 Layers Of Competition In Value Chains

Given the above analysis however, we can see that competitive analysis may be more appropriate at a lower level of detail, where pricing premiums can be measured and modeled.

4.1.4. Important Outputs and Inputs

One perspective on the job of the architect is to allocate the outputs of the organization to maximize inputs, as shown below in the diagram.

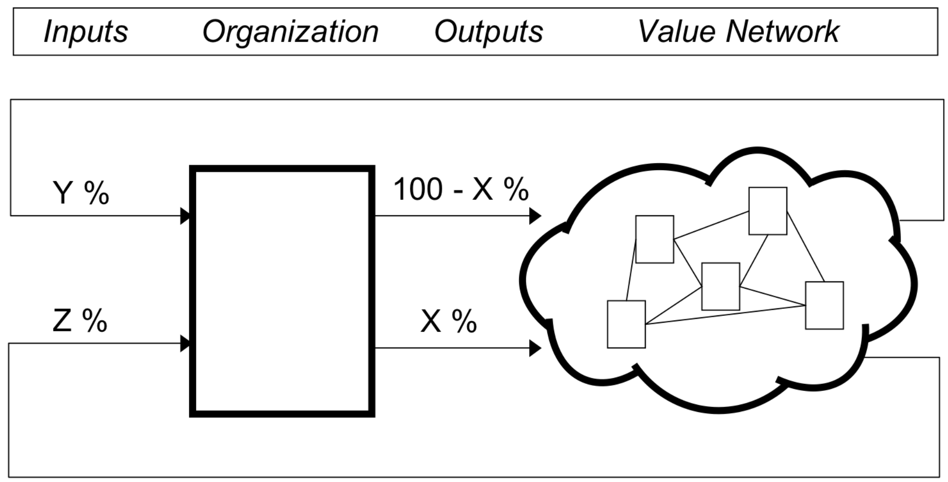


Figure 32 Outputs As Decision Variables Controlling Inputs

This section provides specific answers as to how this methodology informs that question. We can begin to answer this question by constructing the influence matrix A shown below, where individual entries A_{ij} contain all paths from O_i to I_j .

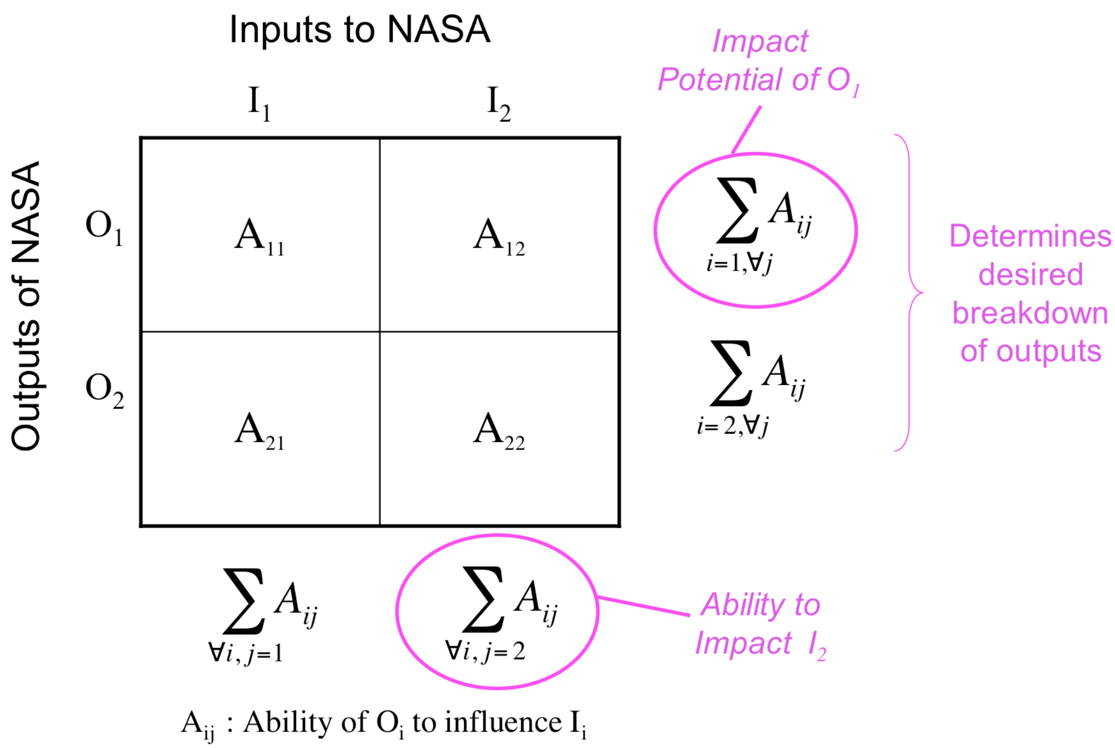


Figure 33 Decomposition Of Value Network Into An Influence Matrix

Having constructed A, note that the individual entries are not directly of interest. It is the allocation of outputs of the organization that is important. This breakdown of outputs can be determined by summing across each row of A, which provides a value of the impact potential of each output. This sum already incorporates how important the input is to NASA!

This matrix also provides a methodology for understanding how well the organization can expect to influence its inputs. Summing down the columns of A captures all possible paths in the network that lead to that particular input.

The following subsections illustrate how these measures can actually be created and interpreted.

Important Outputs

Rather than creating the matrix A then summing columns or rows, it is possible to jump straight to the answer by creating a sum over all loops that contain the benefit flow in question. However, given that the total number of loops in a sample is variable, a normalization is necessary. I propose normalizing by the sum over all loops, such that the sum under the weighted outputs curve sums to 1.

$$OOL(o) = \frac{\sum_{i \varepsilon O} r_i}{\sum_{\forall i} r_i}$$

where: OOL = Output Occurrence In Loops
r = rank of loop
o = the set of all loops that contain the output
i = loop index

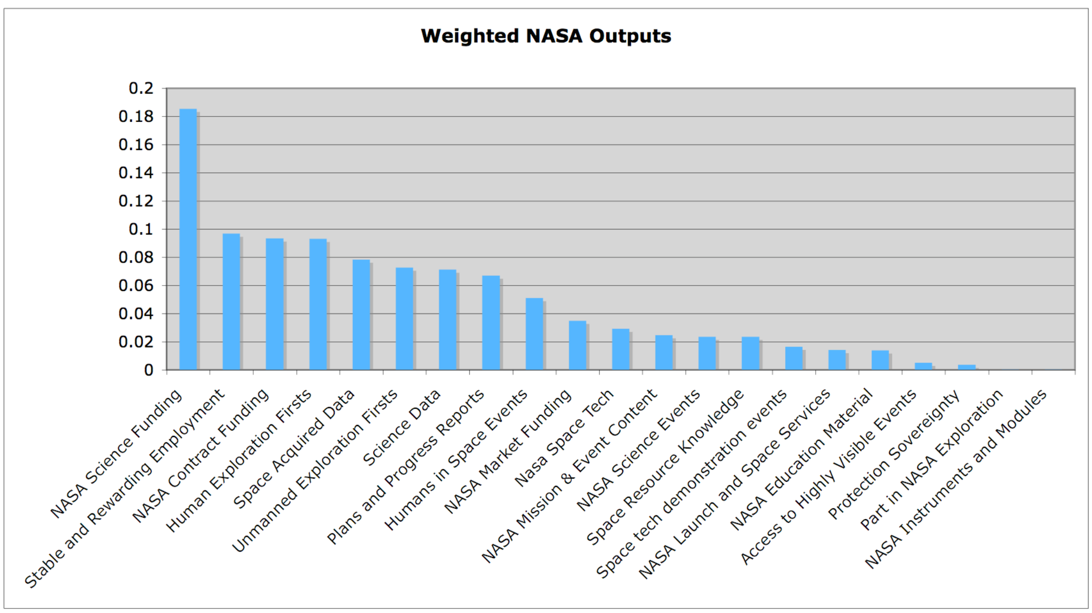


Figure 34 Weighted NASA Outputs

This graph is one of the most important outputs of the model, in that it provides an indication of how the organization should align its outputs to create the strongest case for feedback loops. This graph can be used in two fashions:

1. **Comprehensive:** One should measure the architecture on its distribution of outputs to be aligned with this graph.

2. **Differential:** Once the architecture has been designed, this graph provides the architect with the most highly leveraged outputs for use in adjusting feedback loops to compensate for the value flows where the architecture is less strong.

> **Principle**
> Weighted outputs provide an indication of how the organization should align its products to create strong feedback loops to its inputs of importance.

In general, I would characterize the outputs as uncontroversial, with a few exceptions I will note below. Similar attributes (like NASA Contract Funding and NASA Market Funding) maintain their relative rankings as expected. Stable employment again ranks high, as we would expected from the ranked loops. Exploration Firsts are also ranked highly, which matches the goals respondents chose in the surveys, as highlighted earlier.

It is interesting to note that Science Funding figures so prominently in NASA's outputs, and yet Science is at best an average stakeholder. First, we note that in this model, the Science community (including scientists inside within NASA), has been abstracted to a group outside NASA. Therefore, Science Funding is one of the key methods by which Science Knowledge is stimulated. Second, Science Funding is more powerful than the other major NASA input to Science (Science Data), because Science Funding stimulates all three Science internal assets (Community, Technology, and Knowledge), whereas Science Data stimulates only one (Knowledge).

It is also interesting to note that Space Acquired Data ranks slightly higher than Science Data. The distinction between the two is that Space Acquired Data focuses on measurements useful for design purposes, which might not otherwise merit scientific attention. Examples include calibration of radiation models or re-entry models. Space Acquired data is present in fewer loops, but they are on average shorter than Science Data loops. For the relative funding for the two sources from NASA, and the fact that Science Data is a broader categorization, I might have expected Science Data to come out higher. The use of a high detriment weighting could potentially be responsible for this relative bias on applied outputs.

NASA Launch and Space Services ranks comparatively low. We can ask the question of whether this can be attributed to the low input value (which might be biased by the current unavailability of launch services from NASA), or whether this is a reflection of structural phenomena in the model. We can see from the graph below the discrepancy between the Kano-Importance Data (marked Kano for brevity) and the Loop Data. Specifically, the Kano-Importance Data shown here represents the average of the Kano-Importance values for all stakeholders who receive the output. I have simply renormalized the loop data to the greatest individual value, rather than using the sum over all links to normalize.

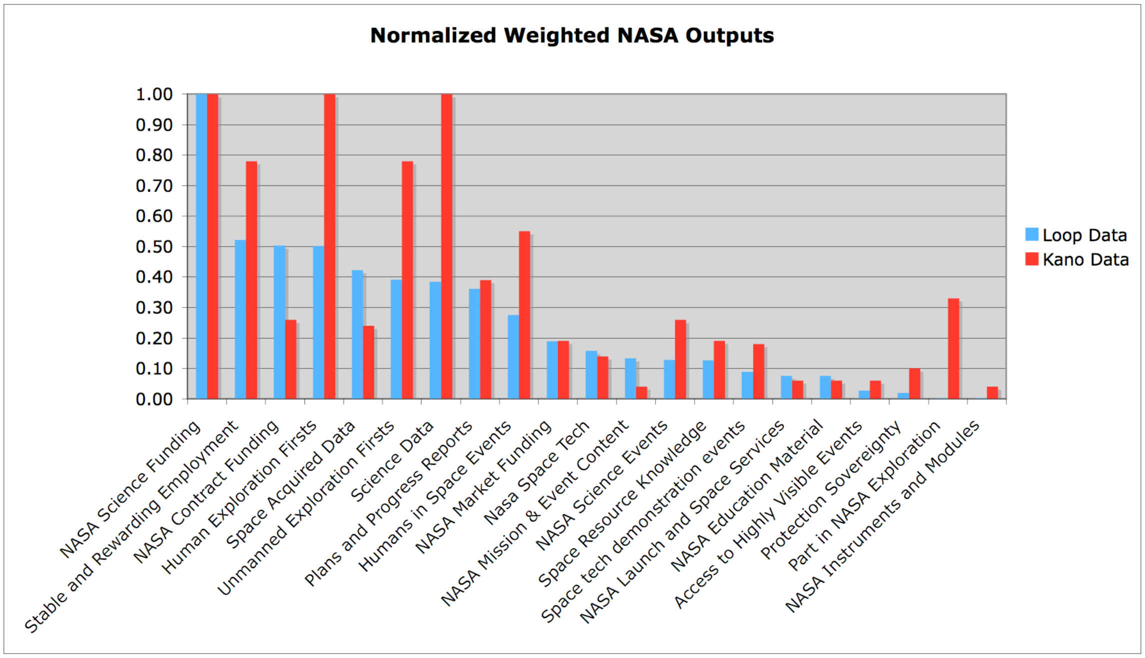


Figure 35 Comparing Weighted NASA Outputs Against Kano Importance Data

The above graph shows that NASA Launch and Space Services' low ranking results from it initial value. The rationale for the initial value was that each of the clients receiving this service has moved to alternative sources (Air Force to EELV, International Partners to Russian launches), to minimize the detriment associated with not having launches, with the exception of modules for the International Space Station.

Discrepancies where the Loop data is significantly lower than the Kano-Importance data result from weak loops. We can see in particular that the outputs that transit through the Media all exhibit this phenomena. Science data also shows poorer loop performance than would be expected by Kano, perhaps reflecting the tenuous relationship the pure sciences have had with applied science. These discrepancies indicate that the network model is producing a different answer than would be gained of only examining direct transactions. In the case of the media and science, I believe this is an accurate trend.

The most stark contrast, in percentage terms, comes from NASA offering Participation in Exploration Missions. I have already highlighted that the model structure was intentionally designed to force international agreements to be negotiated between governments, rather than at the agency level. However, anecdotal evidence would suggest that there is a significant amount of inter-space agency dialogue that sets the tone for international collaboration, before, during and after the formal international agreements. This suggests that there are more direct loops by which NASA can influence international partners, which are being overly penalized by the structure I created. Possible future solutions would include changing the stock structure within International Partners, or allowing loops which visit the same stakeholder twice.

The astute reader will notice that some loops have higher values than the original Kano value. How is it possible to have a decrease in the loop value? To be rigorous, I am comparing similar but different scales that happen to have the same range. The loop values are a sum of the loop products, weighted by rank, as compared to the pure link values. Therefore, a loop will exceed its starting link value when there are multiple loops starting with that link which are ranked highly. There is also a small averaging effect, whereby averaging across different stakeholder preferences, I have represented a slightly different Kano value. However, this would only be a problem if the one link that is furthest from the average was also the only one to be associated with strong loops, which is unlikely.

Taken as a group, flows with high positive discrepancies highlight structure in the model that acts to boost a link's importance. For example, NASA Contract Funding exhibits this behavior, even without including an economic multiplier on government spending.

Important Inputs

Switching focus to NASA's inputs, the exact same procedure is required to rank the input flows by their presence in important loops.

$$IOL(I) = \frac{\sum_{i \varepsilon I} r_i}{\sum_{\forall i} r_i}$$

where: IOL = Input Occurrence In Loops
r = rank of loop
I = the set of all loops that contain the input
i = loop index

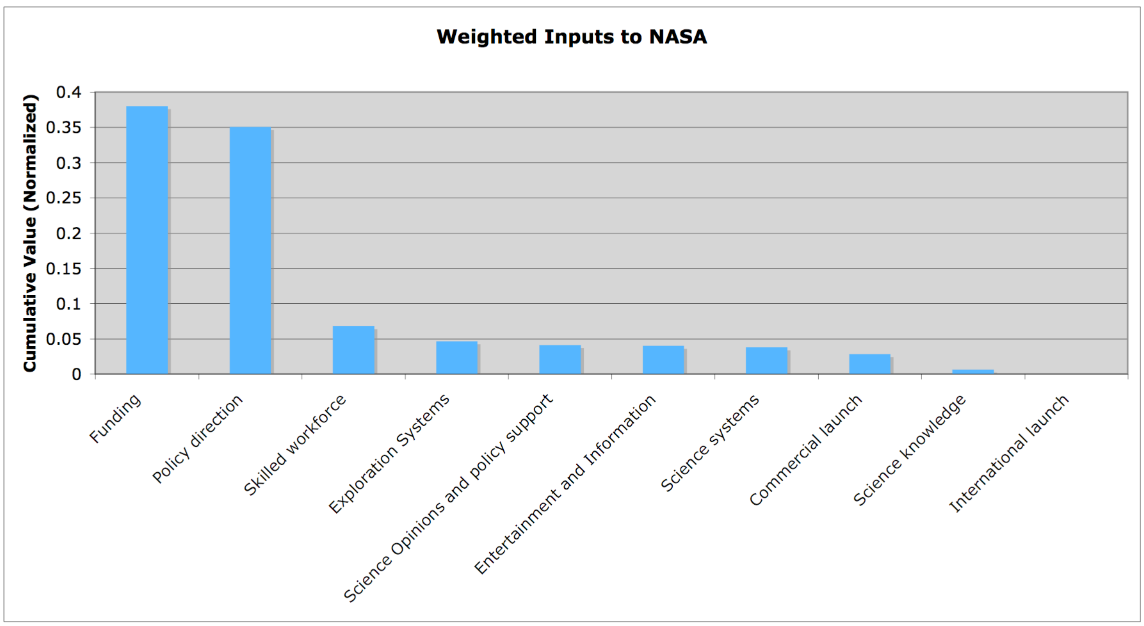


Figure 36 Weighted Inputs to NASA

The results here are relatively straightforward. NASA has the greatest dependence, but also the greatest possible influence on, the two inputs it receives from the Executive.

It is interesting that in the aggregate, the model indicates NASA values Science Knowledge at a relatively low level, despite Science Knowledge's impressive role an enabler for other stakeholders in the model. It is worth reminding the reader that this model does not incorporate an internal model of NASA. The likelihood is that the external inputs which serve to provide both outputs as well as foster internal capabilities (like Science Knowledge) would see their rankings improve dramatically if an internal model for NASA were incorporated.

Examining the discrepancies between the Kano-Importance Data and the Loops Results, we can clearly see that this behavior was not programmed in by the link values.

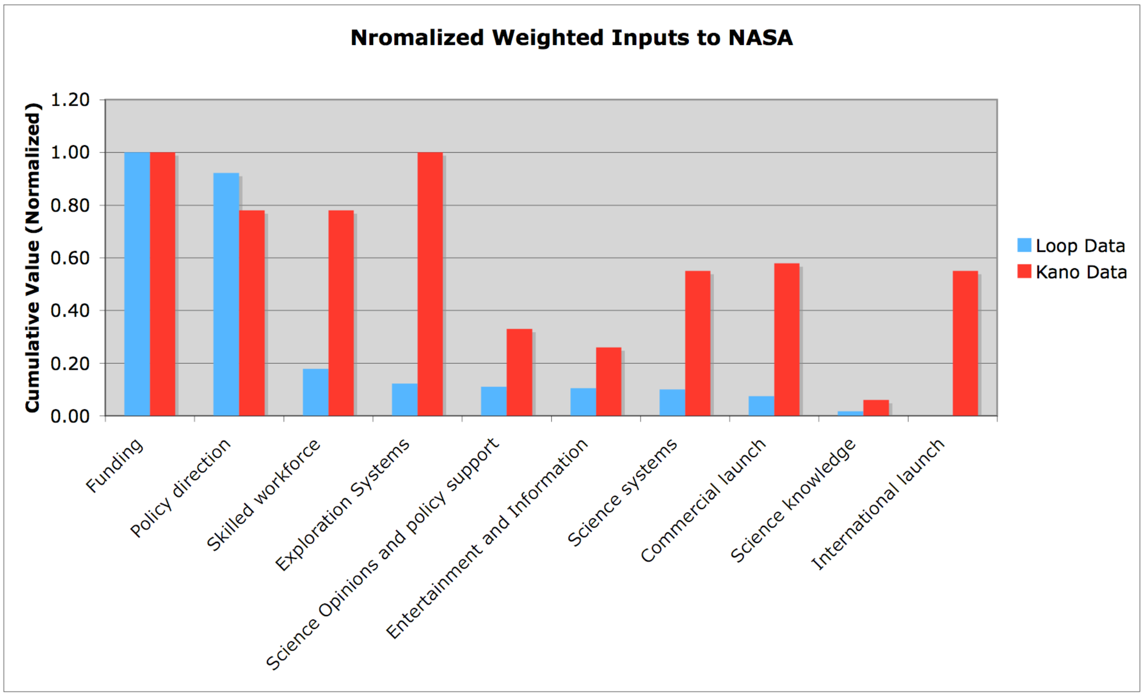


Figure 37 Comparing Weighted NASA Inputs Against Kano Importance Data

4.2. Sensitivity to Numerical Choices

Having now thoroughly examined the potential outputs of this type of network stakeholder analysis, it is necessary to examine how sensitive different parameters are to the numerical modeling decisions made.

First, I examine whether a multiplicative rule forces a correlation between short loops and high average loop value. Second, I examine whether there is a similar correlation between short loops and low loop rank, where the rank is the ranking of all feasible loops in the network model.

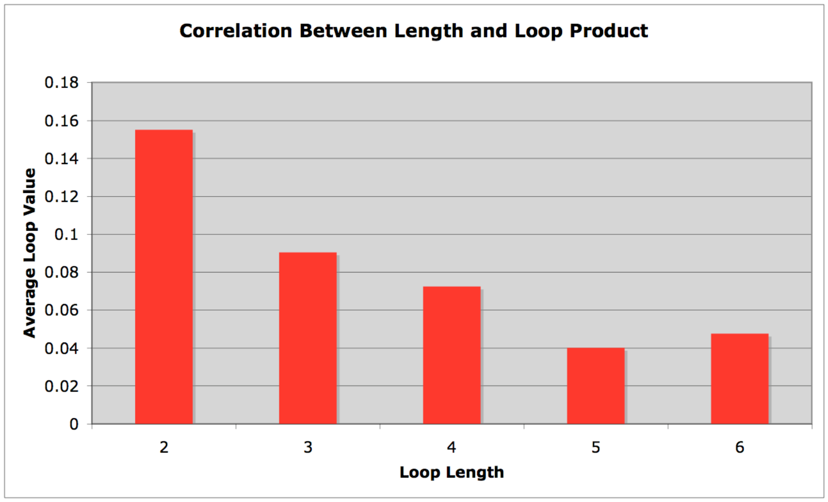


Figure 38 Correlation Between Loop Length and Average Loop Value For V > 0.01

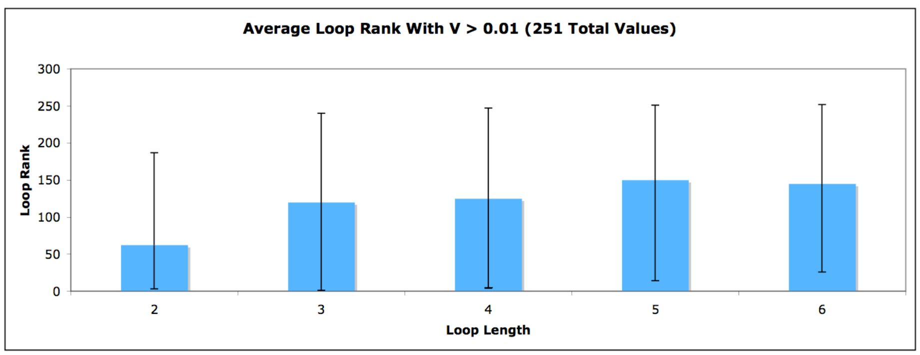


Figure 39 Correlation Between Loop Length and Loop Rank for V>0.01

It appears there is a strong correlation of loop length with average loop value, but a weak correlation with loop rank (with max and min rank shown by error bars). We can see that the highest loop rank is somewhat bounded based on loop length.

What we can't observe are the number of possible loops in the system for each loop length, because I have dynamically bounded the model based on a minimum loop value. For example, there are 27 possible loops of length 2 in the model (which I can observe because this isn't computationally intensive), 22 of which are captured by using $V > 0.01$. If the distribution of loop lengths was anything but flat (i.e. if there were more loops of length 3 than of length 2), then we would see it reflected in the above graphs, regardless of the numerical methodology (because the average loop value of the most common loop length would dominate). As I scale the length of loops up, I would expect to see significantly more possible permutations, which would decrease the average loop value, and increase the average loop rank. Unfortunately, because it is not computationally possible to enumerate all of these loops, I can't plot those curves.

However, I can compare the values of the top 20 loops in each length category, in order to normalize for loop lengths that are more prevalent. Using this data, it is clearer that loops of length 2, 3 and 4 do not exhibit a length bias for average loop value , but that there is some question for loops of length 5 and 6.

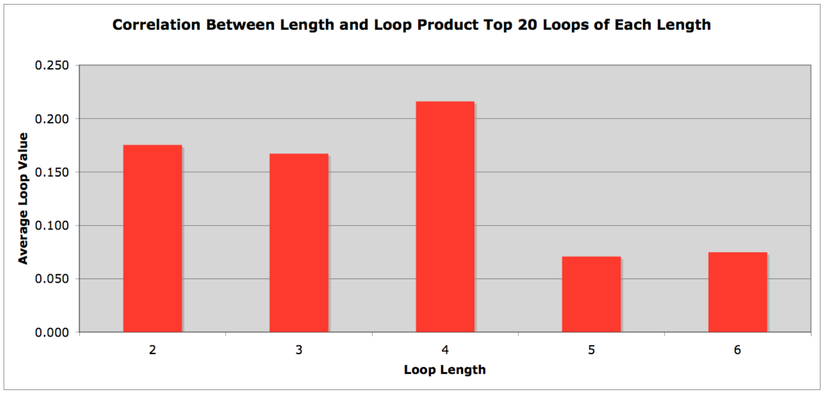


Figure 40 Correlation Between Loop Length and Average Loop Value for Top 20 Loops of Each Length

It is interesting to note that the dispersion in loop ranks is lowest for length = 4 (shown in the figure below), which was also the average length for the loops I generated for comparison before the model. This may reflect an additional cognitive bias in building the model, in that four links was roughly the 'expected' length.

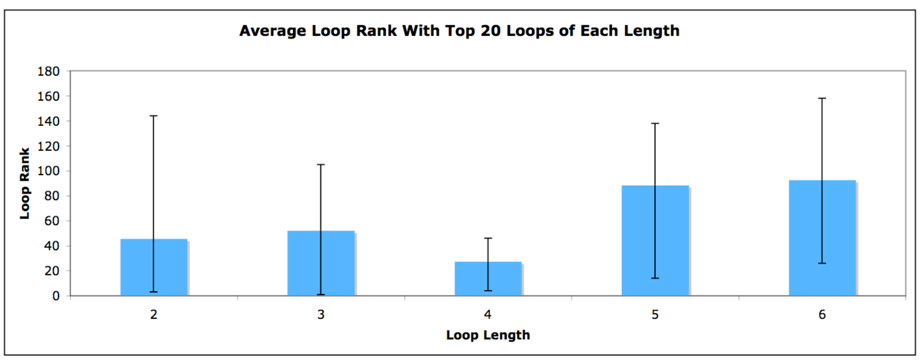


Figure 41 Correlation Between Loop Length and Loop Rank for Top 20 Loops of Each Length

Having identified that there is some correlation of value with length, we can ask the question "Is this reasonable?". Experience would suggest that it is difficult to be aware of much more than 2 transaction ahead or behind a particular stakeholder. This would suggest that loops of length greater than 3 will contain stakeholders who are unaware of the root provider of benefit. Unfortunately there are few tests I can conduct to verify this idea, so this will have to be accepted as a potential difficulty with the model. One alternative solution would be to run both multiplicative and additive rules on the model, and then derive the final rankings as a combination of both.

Kano Multiplier Sensitivity

When this numerical methodology was created, the Kano Multiplier was chosen to be 3, but I expressed a desire to perform sensitivity analysis on it. This section applies a Kano Multiplier of 2 (KX2), as well as a linear Kano scale (entitled KX123), and then looks at how loop length and rankings change. Through all of these tests, a constant dynamic bound of V > 0.01 is used.

Three comparison statistics were created. The first measures the percentage overlap of loops between two sets of rankings. Therefore, if four out five loops are common to both sets, but a fifth is unique to each set, the overlap would be 80%. The second measures the absolute distance (difference in rank) between the same loop in two sets. The distances for all common loops are then averaged to create a summary statistic. Finally, I also capture the maximum distance within a set, which is obviously bounded by the size of the set (two ranks can't differ by more than 250 if there are only 250 loops in each set, because the loop must be present in both sets to begin with).

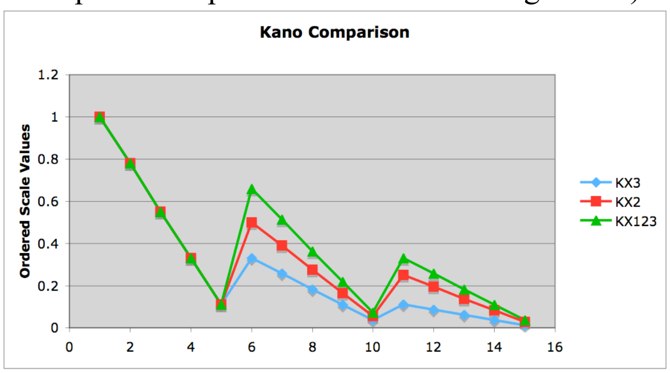


Figure 42 Kano Importance Values With Different Kano Multipliers

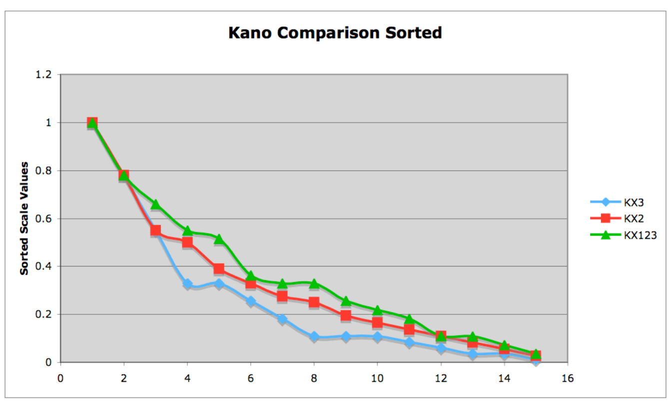


Figure 43 Kano Importance Values Sorted

To begin with, the distributions of link values are shown above for comparison. The first figure is kinked where the distribution moves to a lower Kano level. We can see that the higher the Kano Multiplier, the smaller the area under the curve.

Table 7 Comparison of Model Output Under KX2 and KX3

KX 3 vs. KX 2	Percent Overlap	Average Distance	Max Distance
Top 5	100%	0	0
Top 10	70%	0.6	1
Top 20	75%	2.0	8
Top 50	98%	3.6	12
Top 250	94%	14.7	90

It is interesting to note that much of the re-arrangement occurs within the Top 50, which corresponds roughly to the thick part of the original rankings curve. If the model is used to focus on a certain subset of important loops, it would therefore be advisable to choose the Top 50 over the Top 20.

Similar behavior is observed for the linear Kano scale, with slightly greater deviations.

Table 8 Comparison of Model Output Under KX123 and KX3

KX 3 vs. KX123	Percent Overlap	Average Distance	Max Distance
Top 5	80%	0	0
Top 10	70%	0.3	1
Top 20	95%	2.4	11
Top 50	94%	1.8	26
Top 250	92%	20.8	122

Note that the average value of loops increases, as the tradeoff with Kano is not as steep. We can see that the difference between the sets is most pronounced for shorter loops. Therefore, the behavior of loop value with length is relatively insensitive to the choice of Kano multiplier.

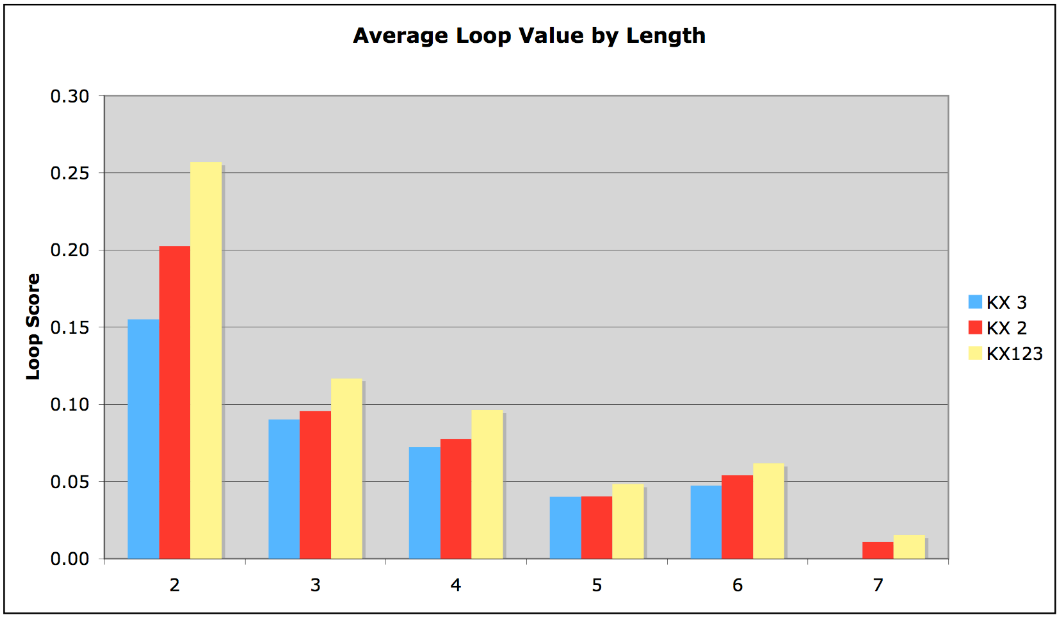


Figure 44 Sensitivity of Average Loop Value By Length To Kano Multiplier

Most importantly, how does the prioritization of stakeholders change? The graph below shows that the change is almost negligible. This suggests that we are seeing small changes in rank between different loops, but that the normalization chosen (sum of all loops) is doing its job.

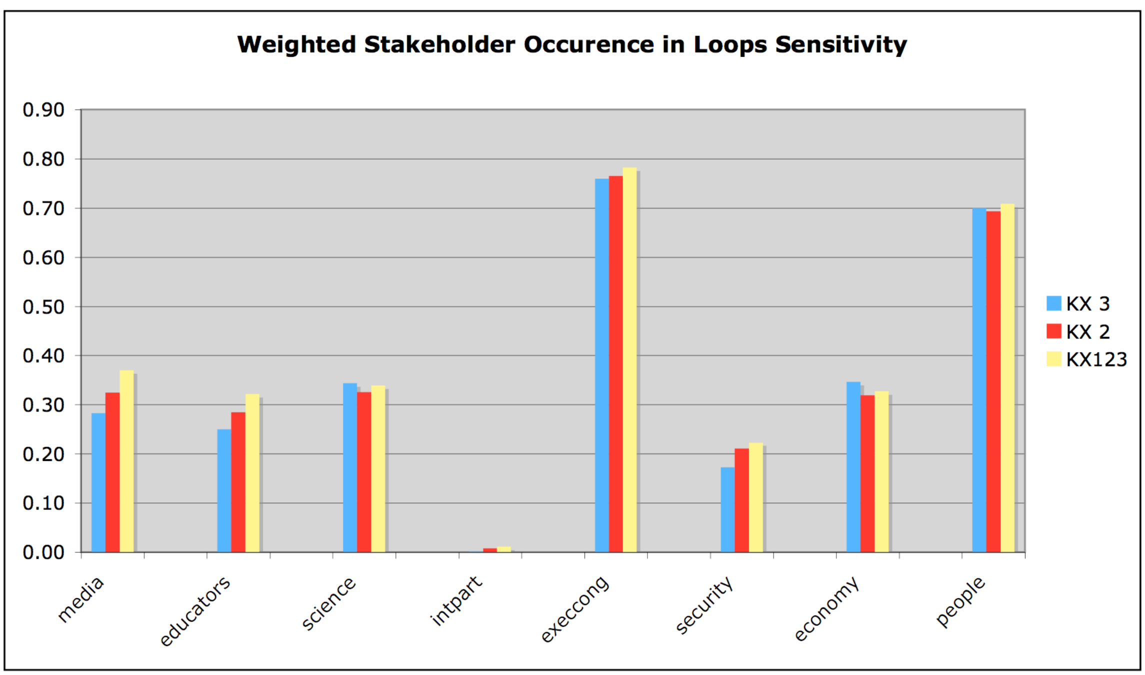


Figure 45 Sensitivity of Stakeholder Occurrence To Kano Multiplier

Kano Importance Correlation

I originally suggested that the Kano scale would not necessarily be independent from the Importance scale. In the charts below, this phenomena is examined. In order to allow for small changes in individual decisions, I've bucketed the Importance scale in 3: *Low Importance*, defined by the points "Not at all important" and "Somewhat Important", *Important*, defined by the points "Important", and *Very Important*, defined by the points "Very Important" and "Extremely Important".

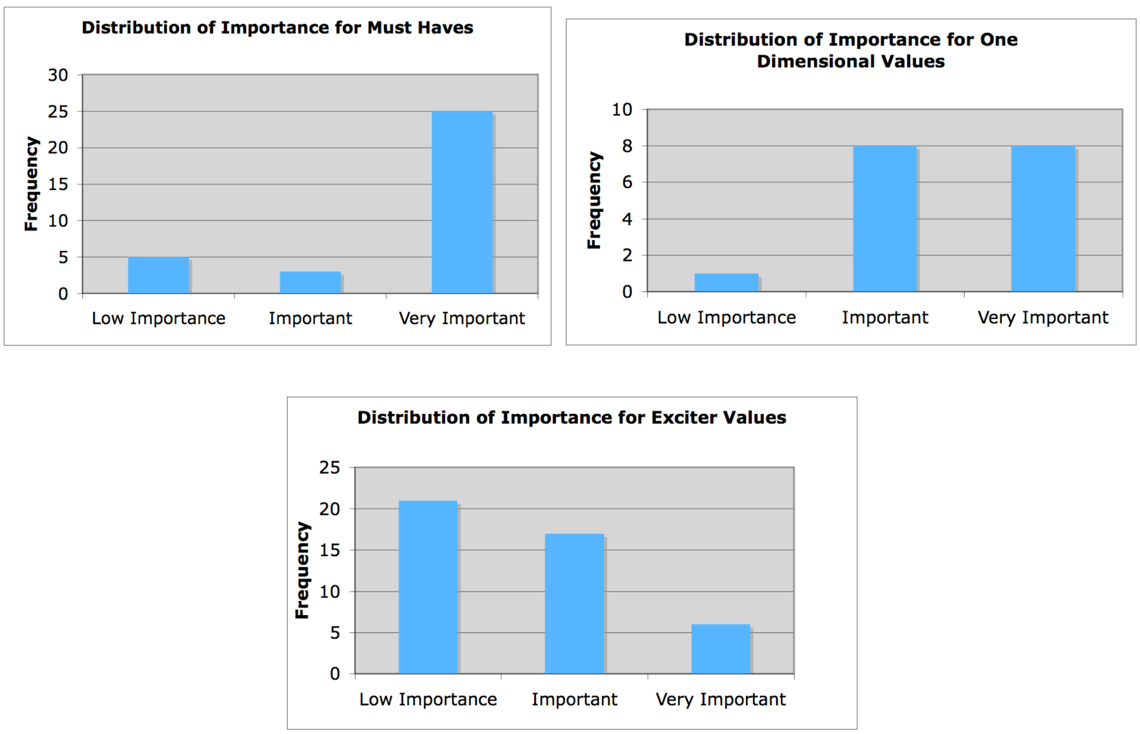


Figure 46 Correlation of Importance Scores to Kano Scores

The correlation is clearly the strongest for Must Haves, and the weakest for Exciters. However, in each case, there is a distribution across the full breadth of the Importance scale. This indicated that different information is being captured in each. In a manner of speaking, the Importance scale allows the user to highlight realistic priorities, or flows where there is little expectation of changed in flow rate. The Kano data allows the user to specify official policy information, in a sense. For example, 'Protection Against Claims Of Sovereignty' might be a flow that the government might not be willing to lose (Must Have), but in terms of an operational agenda, it might rank low on the important scale.

4.3. Testing The Output Variability Assumption

When designing the loop methodology, the reader will recall that it was assumed that inputs and outputs are variable. The purpose of strong loops in this model is to identify outputs to modulate, so as to impact inputs. Therefore, this section performs a brief check to ensure that outputs and inputs are in fact variable.

It is possible to quantify many of the links in the model, either directly or with indicators. However, it quickly became clear that the inputs and outputs of NASA were the mostly easily quantifiable, and also the best tracked, of all the flows in the model. This is not because economic, education and security indicators are no tracked. Rather, the specific impact of NASA actions can be difficult to track. Some localized studies have been performed, however. For example, many centers publish their estimation of impact on the local economy, including economic spending multiplier effects[51], but none of this data is aggregated nationally, and is therefore not immediately useful. The outputs and inputs for which appropriate data could be found is shown in the table below.

Table 9 NASA Inputs and Outputs For Which Link Data Is Provided

Outputs		**Inputs**	
Access to highly visible events		Commercial launch services	☑
Human Exploration First Events	☑	Exploration systems	
Humans in Space Events	☑	Funding	☑
NASA contract funding	☑	International launch services	☑
NASA education material	☑	Internationally provided space systems	
NASA instruments and modules		Media Entertainment and Information	
NASA launch and space services	☑	Participation in international exploration mission	
NASA Market funding		Policy Direction	
NASA Mission and Event Content		Science knowledge	
NASA Science Events	☑	Science opinions and policy support	
NASA science funding	☑	Science systems	
NASA space technology		Skilled and motivated workforce	
NASA Space technology demonstration Events			
Participation in NASA Exploration Missions			
Plans and progress reports	☑		
Protection against claims of sovereignty in space			

Science data	
Space acquired data	
Space resource knowledge	
Stable and rewarding employment	
Unmanned Exploration First Events	☑

Financial outputs are the most easily reported, and the most stable of outputs. NASA Science Funding is calculated from the NASA Annual Procurement Report[52], which has buckets for Educational and Non-Profit Institutions. As such, Science Funding to internal NASA scientists or industrial scientists is not reflected here. NASA Contract Funding is also calculated from the NASA Annual Procurement Report, using the 'Business Firms' bucket. NASA Educational Funding is derived from Education Programs in the budget breakdown by enterprise in the NASA Performance and Accountability Report (PAR)[53]. NASA Launch and Space Services is calculated from the PAR statement of intragovernmental revenues, which includes military and civilian agencies - the most prominent of which are the Air Force and the Dept. of Commerce (NOAA), respectively. NASA Employment is calculated from a published survey of NASA average salaries[54] multiplied by the number of employees, as the PAR does not explicitly break out salary costs.

It can be seen from the graph below that many of the budgets seem to be calculated as a relative percentage of the previous year's budget. However NASA Contract Funding and Science Funding both show broader variability, the former likely the result of Return to Flight spending, and the latter as a result of increased exploration spending.

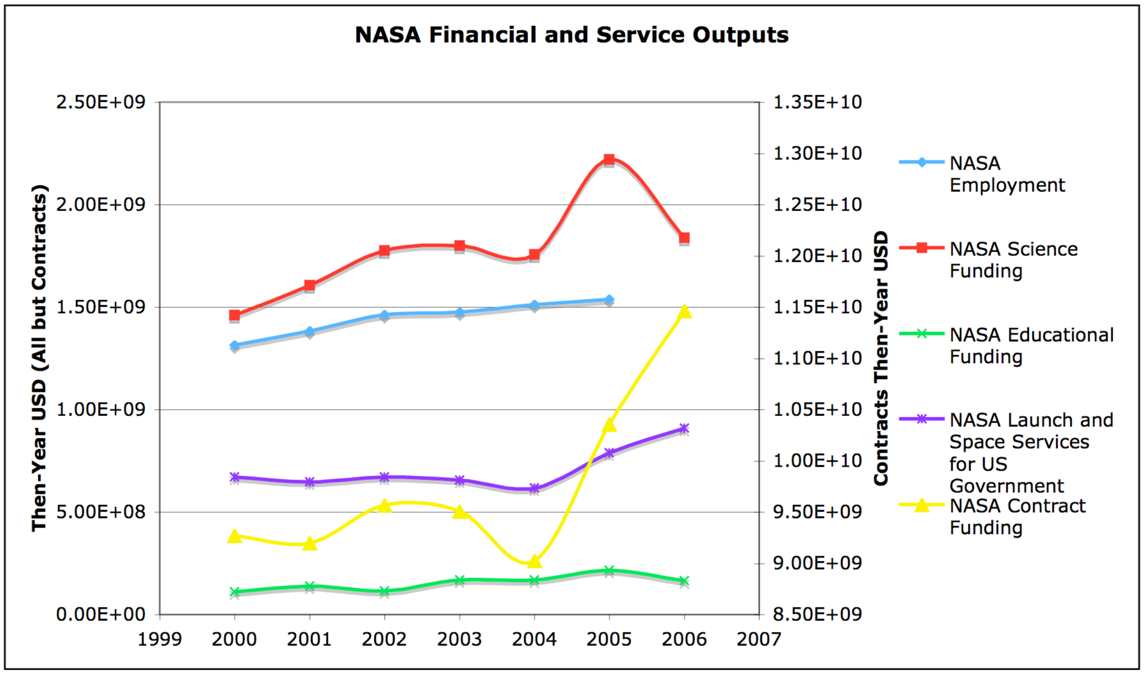


Figure 47 NASA Financial and Service Outputs Over 6 Years

The distribution of NASA Events shows significantly more variability. For the purpose of this study, only missions and launches were counted, rather than attempting to track individual news reports related to missions. Humans in Space events is calculated as Shuttle and Soyuz launches. NASA Science Events are calculated as a Science Missions launched, not including International Missions with NASA equipment on board. Surface missions are counted as Unmanned Exploration rather than Science, for bookkeeping purposes. Humans Exploration Firsts are defined as new planetary or orbital missions, none of which have been executed over the timeline examined.

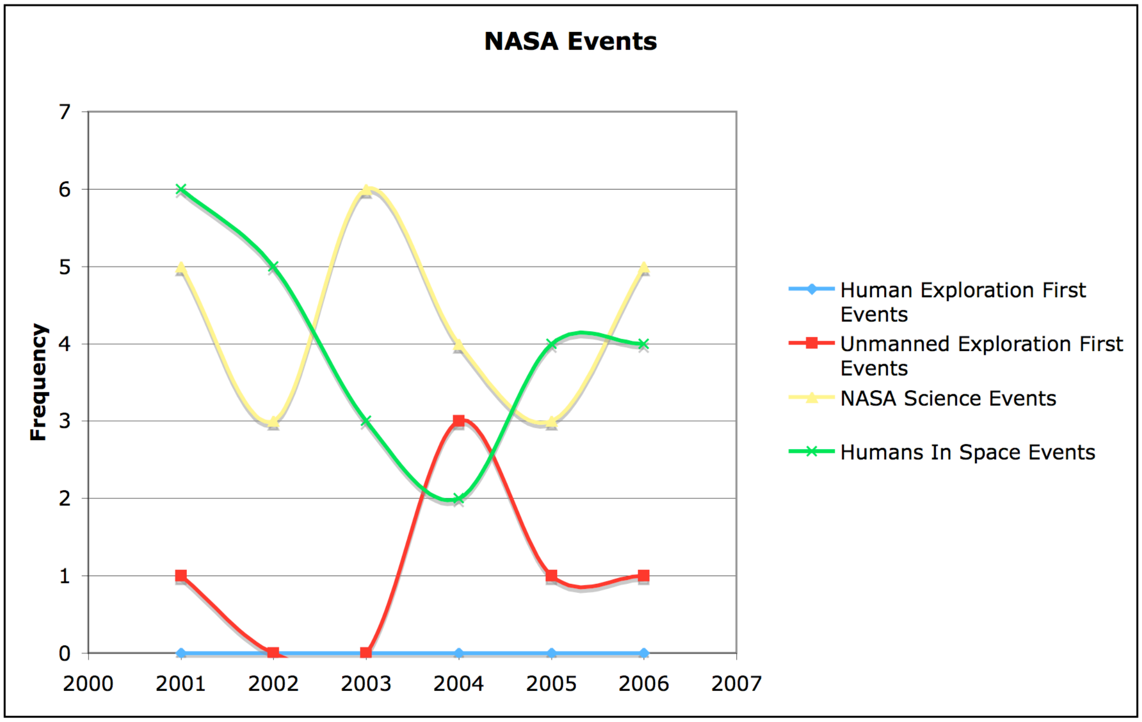


Figure 48 NASA Events Over 5 Years

NASA Plans and Progress Reports is inherently a lumpy measurement, because major initiatives arise on a decadal basis, but individual meetings and consultations take place on a daily basis. Two indicators are given below, which try to strike a balance of detail. First, formal congressional hearings per year is . Second, NASA press releases per year are also shown. While the most common type of press release focuses on a current mission, many are also provided on future missions and science data or imagery releases.

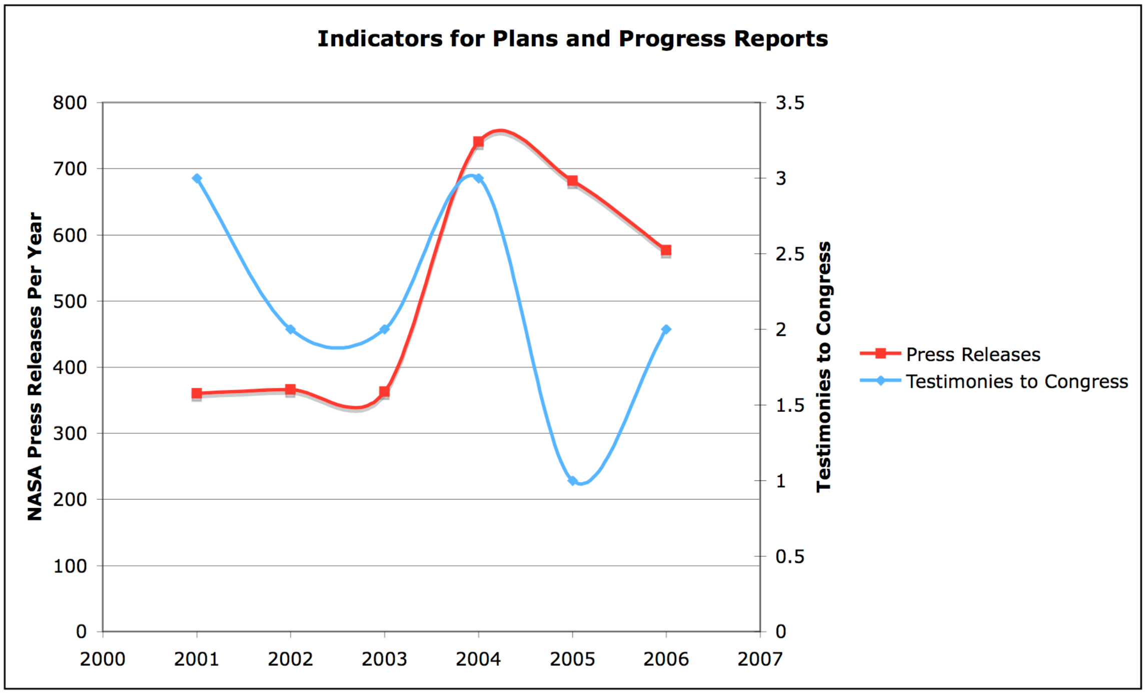


Figure 49 NASA Plans and Progress Reports Over 5 Years

Thus far, all of the graphs shown track NASA Outputs. The graph below shows the NASA Inputs that can be readily tracked (only 3 of 12 total inputs), in addition to the redundant inputs from the direct transactions like Exploration Systems (the same value as Contract Funding) and Skilled Workforce (the same value as NASA Employment output). We can see that NASA Funding does not vary significantly, despite annual optimistic projections or historical comparisons to the Apollo funding. However, both commercially-purchased and international launches do vary somewhat, although the data is admittedly lumpy due to a dependence on mission timing.

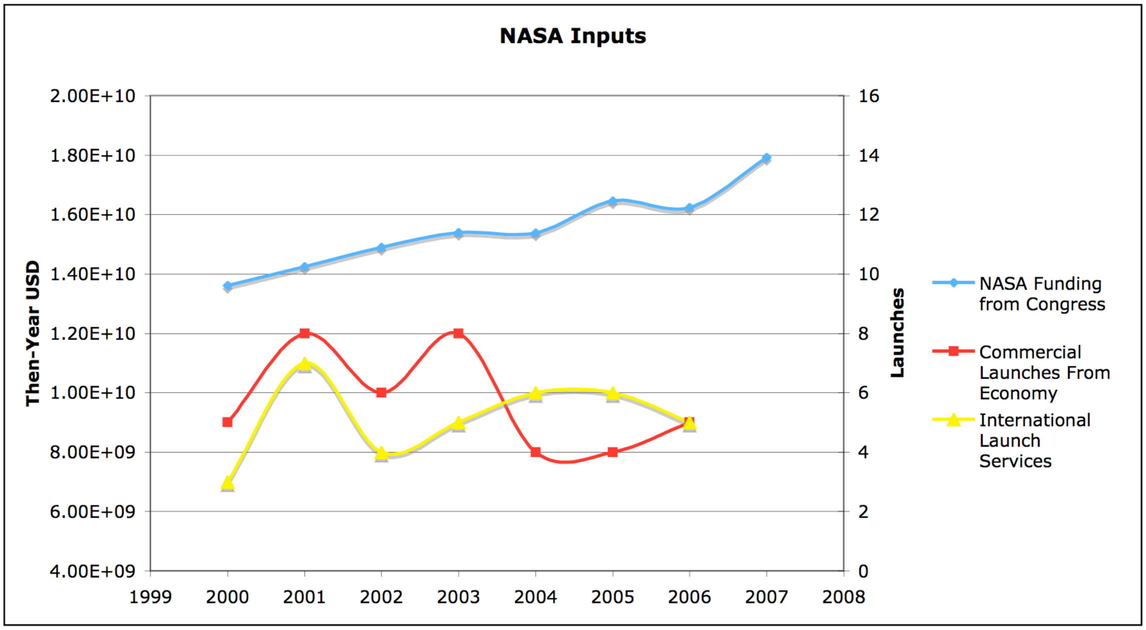


Figure 50 NASA Inputs Over 6 Years

Overall, funding shows the least volatility over time, and events show the greatest changes. However, funding represents the nearest term decision in many cases, whereas events arise out earlier decisions and effort. This data is sufficient to conclude that there is *some* variation in outputs and inputs. This data is *not* sufficient to determine whether past architecture had a causal effect on outputs, because the time series is not long enough, not all outputs have been captured, and I haven't defined what the relevant exogenous factors in the NASA inputs might be.

Given that NASA has shown variability in outputs, we next need to examine the idea that different architectures can produce different outputs.

4.4. What Questions Have I Not Answered?

Notice that I haven't answered the question "What loops produce the most value?", because there are no actual events. However, this analysis suggests that if these loops were allowed to run over multiple cycles, they would provide the best chance for modulating outputs to create the best reinforcing loops. I have also included a discussion which suggests that a selfish bureaucracy produces the most value to its stakeholders in the longer term, provided there is oversight to ensure that it doesn't extract rents.

To these ends though, I also haven't answered the question of whether NASA is the best provider of value per dollar relative to other agencies that produce the same outputs. There is an effort to value inputs relative to the availability of other sources, but all competing flows are not illustrated in the model, given the difficulty in setting bounds on what else is 'relevant'.

I also haven't answered what NASA's top priority should be, if it could do only 1 thing. This creates some difficulties relative to survey data, but I can make some assumptions to suggest that the top output should be the top priority. Namely, if the ranking scale I used with Kano-Importance isn't saturating (such that the highest priority items aren't sufficiently differentiated), and if we assume (contrary to the earlier analysis on competition) that none of NASA's outputs are irreplaceable, and finally, if we assume that all outputs are independent (i.e. the absence of 1 doesn't handicap another), then we can say that NASA's top output is its highest priority.

I haven't answered what NASA does best currently, or where the biggest value holes are. The analysis performed here was designed to be sufficiently generic that individual programs would fit into the framework, but this analysis was not directly conducted. However, the comparison analysis of NASA's perceptions as compared to survey data does offer some hints.

Finally, I haven't answered how this ties to architecture, which, it so happens, is the topic of the next chapter.

5. Linking Benefit to Architecture

The intent of this chapter is to demonstrate that the benefit methodology created in previous chapters can be used to differentiate between exploration architectures. More specifically, this chapter explores what attributes of architecture can be linked to value, how one might actually implement this link, as well as the relevant operational considerations. Throughout this chapter, the focus is on evaluating architectures for benefit, rather than encoding benefit as requirements.

This chapter provides answers to the following questions:

- ☒ How can we create proximate metrics more systematically?
- ☒ Are metrics a way around goals, or a way to create them?
- ☒ Can we determine a process to more systematically project needs onto goals? Could this facilitate bookkeeping of stakeholder need to goal relations?
- ☒ How can we identify and deal with needs that are congruent, orthogonal, or opposing?
- ☒ How can we deal with uncertainty and likelihood of change in a need?

5.1. Framework for assessing the link to architecture

This section defines the relevant concepts for assessing the link between benefit and architecture. First, three architecting methodologies are examined for their ability to create this link. Second, a framework for assessing the relationship between the two models is created.

This section focuses entirely on 'computing' stakeholder satisfaction, without regard for the realities of an organic decision process. These concerns are then discussed in Section 5.3 .

How do other architecting frameworks create the link to benefit?

Three architecture frameworks were examined for their ability to tie stakeholder considerations to technical designs. The three used were the NASA System Engineering Processes and Requirements[55], the Dept. of Defense Architecture Framework (DoDAF)[56], and the IEEE Standard 1471.2000 Recommended Practice for Architectural Description of Software-Intensive Systems[57]. A brief description of each is given below, followed by a comparison. As these frameworks err on the side of more considerations rather than brevity, one certainly has to question whether the processes are all realistic. I have therefore placed emphasis on guidelines for dealing with stakeholder needs, and the sector of the architecture that receives stakeholder-derived information.

NASA's Framework is most traditional system engineering representation of the three. Indeed, it is not explicitly an architecture framework, but rather a set of processes.

The framework explicitly requires that stakeholders be consulted in order to define "use cases, scenarios, operational concepts", "needs, wants, desires, capabilities, external interfaces, and constraints", as well as "expectations" as a function of project phase. These stakeholder inputs are assumed to translate directly into technical requirements through a decomposition analysis. However, stakeholder input also forwarded into the validations process, as captured by "Measures of Effectiveness" (as opposed to Measures of Performance), as shown in the diagram below. These MOEs are not elaborated on further in this document.

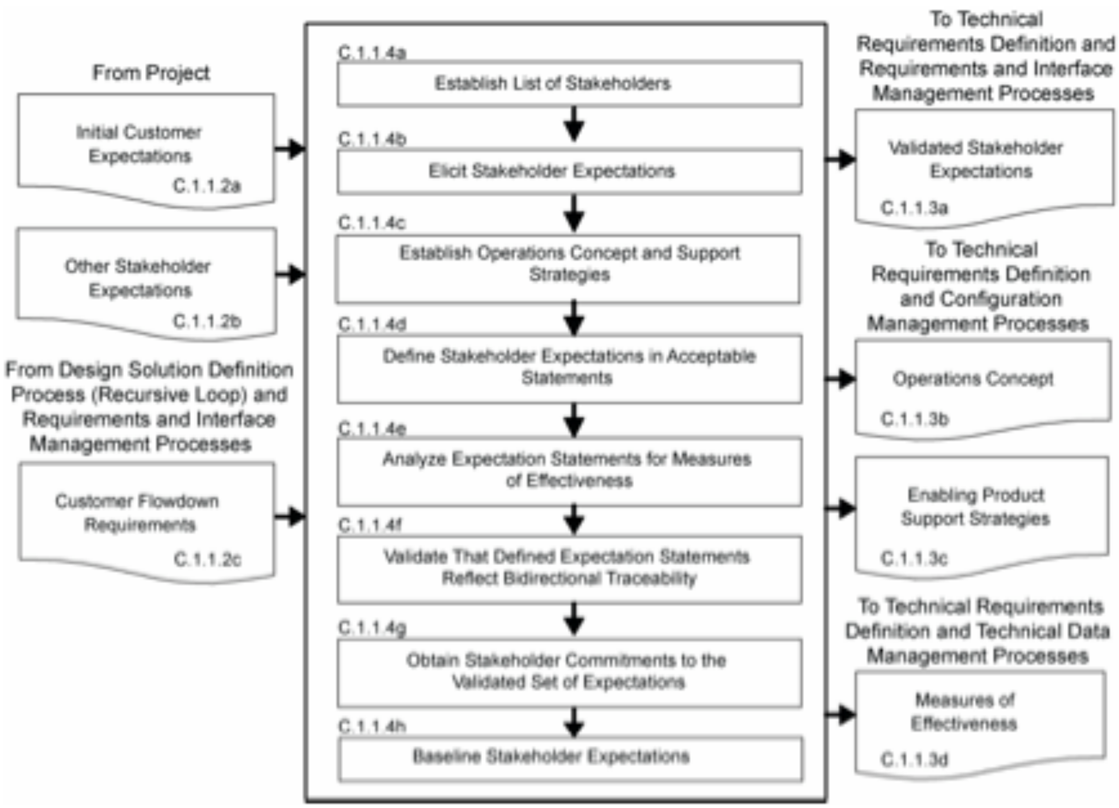


Figure 51 NASA Stakeholder Expectation Definition Process

Putting aside the top-down process, NASA also defines the steps required during the Design Review process. These review guidelines give no direct indication of stakeholder consideration. The Mission Concept Review requires "the need for the mission" and "mission objectives" to be identified – this is suggestive of the technical criteria, although "mission objectives" are not mentioned earlier in the document. The System Requirements Review requires the specification of "interfaces with external entities", and now highlights the multiple needs the mission will serve. The Critical Design Review requires a validation plan, which was earlier linked to stakeholders. All three of these Reviews note that technical requirements must be written and satisfied, but the question of "expectations" that are not well encoded as requirements is not addressed.

This merits particular emphasis – NASA has defined stakeholder preferences as inputs to its process, but has not made use of these inputs at the critical stage, the evaluation of architectures!

The DOD's Architecture Framework is much more extensive. Four architecture "views" are defined, three of which are as shown in the figure below. The fourth view is named the "All View", and includes a high level overview of the purpose of the architecture, and the first layer of information from each of the 3 other views. In particular, the All View captures the relevant goals, constraints and limitations placed on the decision (which could be interpreted as stakeholder needs), as well as the authority for making the architecture decision (which could be external to the architect).

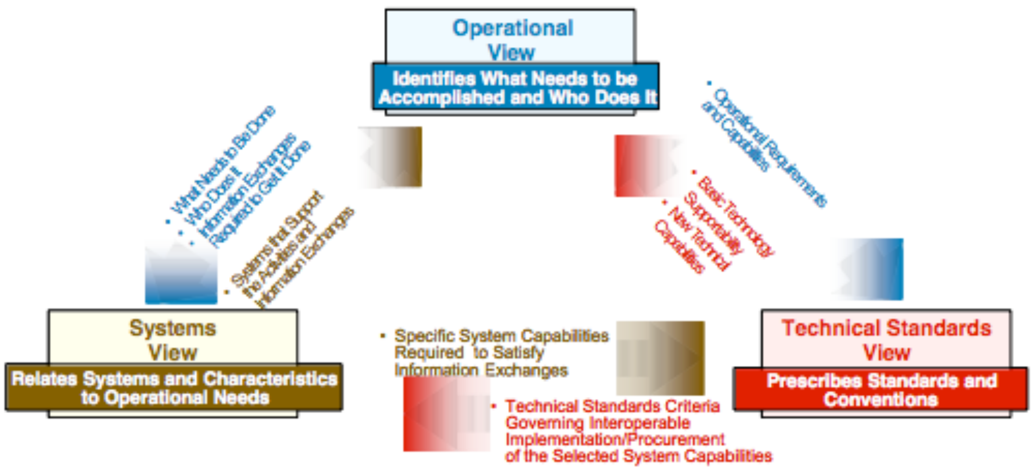


Figure 52 DoDAF Architecture Framework

Fewer descriptive words are used to describe stakeholder input in the DoDAF – "needlines" are simple but profilic, used to describe goods, services, and information provided to key players, illustrated in Operational Views #2 and #3. However, an enormous emphasis is placed on operations and interoperability with systems outside the boundary. These needlines are fed forward into the System View, in System View #1 (Interface Description) and System View #7 (System Performance Requirements).

Relative to the NASA framework, more emphasis is placed on evaluating the architectures against derived criteria. Specifically, the system is validated against Capability Needs, System Performance Requirements, Operational Measures of Effectiveness, and Level of System Interoperability. This emphasis on metrics rather than derived requirements suggests a broader consideration of operational needs.

IEEE 1471 places stakeholders in the most central position of the three frameworks. This is readily seen from the diagram below, given the central placement of stakeholders in the process. IEEE 1471 also casts the widest net in terms of information polled from stakeholders, citing needs and constraints, purpose and vision for the system, feasibility of constructing the system, risks of system development and operation, maintainability, deployability, and evolvability of the system. The IEEE 1471 is also the most generic framework, in that the number of architecture 'views' defined is open to the architect. Two central requirements are imposed on views: Each stakeholder concern must be represented in at least one view, and each view must define what model or process is used by that view. Architectures are then evaluated for their ability to reproduce views, although there are no clear criteria given on how one should match architectures to views. The IEEE 1471 framework is primarily concerned with representation, and as such, little guidance on process is provided. This was to be expected in the software industry, where the design space is typically broader and more versatile than in the hardware and systems worlds.

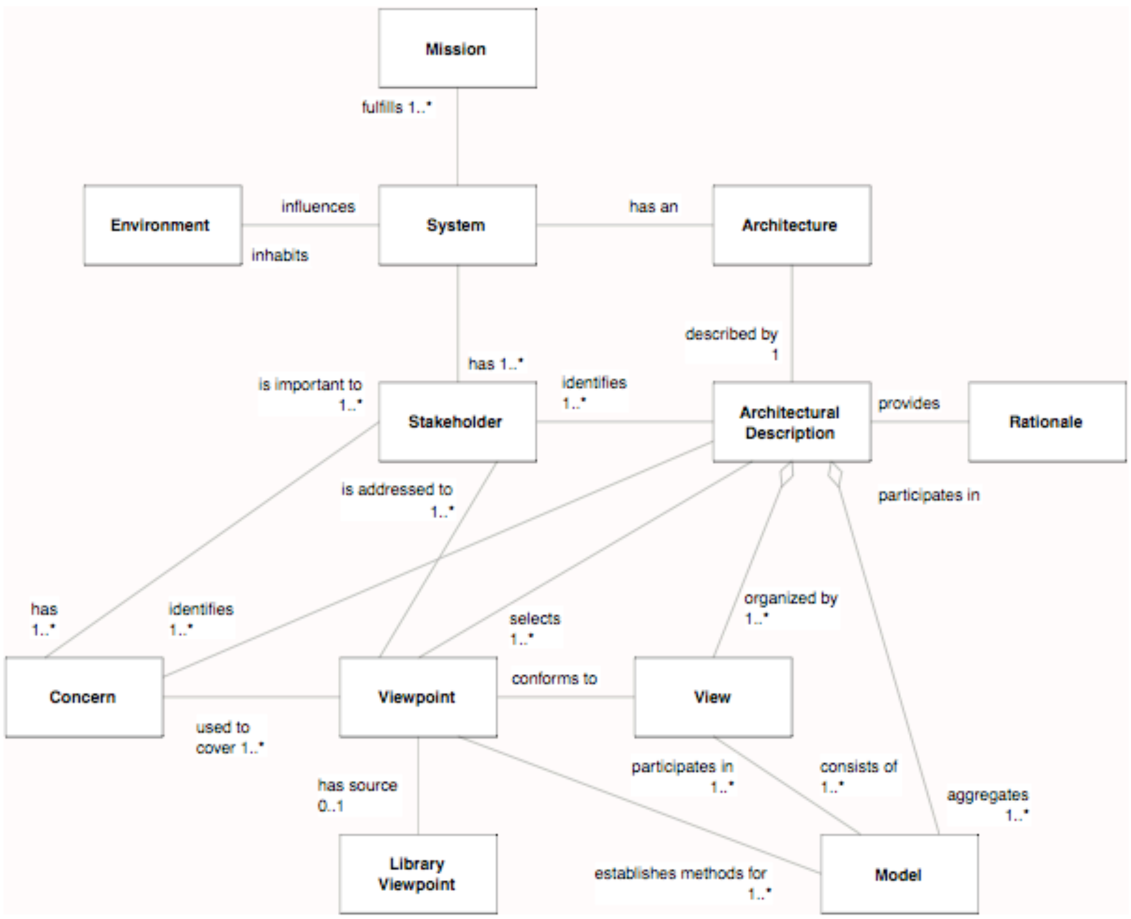


Figure 53 IEEE 1471 Architecture Representation

Notice that DoDAF and IEEE 1471 explicitly evaluate architectures, whereas NASA searches for the architectures that meets all the constraints. All of these frameworks highlights stakeholder concerns, but only DoDAF and NASA define traceability of stakeholder concerns. Of these two, DoDAF defines explicitly how information gathered from stakeholders is translated or used, where NASA only defines this implicitly through connectivity. Notice that NASA and IEEE use many words to define stakeholder input – in practice, it can be difficult to understand how stakeholder 'opportunities / wants / desires' are incorporated into a system model, in that these terms don't necessarily have separate technical meanings.

Principle
Stakeholder inputs should be traceable to metrics and criteria at the architecture evaluation phase

The most telling difference is likely the use of stakeholder concerns in architecture evaluation. DoDAF once again scores highly, whereas NASA is inconsistent. This suggests that NASA does the broadest initial consultations, but is the least responsive on the back-end of the design process, which would square with the level of feedback available to the architect based on completed designs in the military relative to the space agency. However, one must be careful in reading too much from abstracted processes, given that actual design processes are non-linear, iterative, and full of uncertainty.

Note finally that none of the architecture frameworks consider indirect benefit. Clients are identified, and their needs defined, but no one client is defined as the agent of another. Without clear rules for defining benefit propagation, this is to be expected. Further, one would expect this to be a larger problem for NASA than the IEEE, given the scope and public nature of NASA's work.

Having now examined how some other architecture frameworks have considered benefit, I now define a framework for computing the benefit of individual architectures using a benefit network model.

Framework

The fundamental postulate of my work is that the value outputs of NASA can be tied to an architecture model. However, the fundamental difficulty here is that many of the benefits will be produced over decades, so there is significant uncertainty associated with the use of traditional indicators. For example, a traditional indicator for Science Knowledge is scientific papers produced, but there is no way to determine this short of waiting 15 years.

There are three sets of decisions to be made here on the strategy for capturing how different architectures may produce different benefits:

1. **Cardinal or Ordinal?** We could either rank architectures against their ability to produce each value flow (Ordinal Utility), or provide an estimation of the strength of preferences (Cardinal Utility). Note that cardinal utility provides both the ranking that ordinal utility does, as well as more information

2. **If cardinal, real numbers or scales?** Given that we will be creating an abstraction from a technical level within the architecture to a high level benefit delivery, is it reasonable to attempt to tie real numbers to measures. Alternatively, we could have an anchored scale to represent likelihood, which would still express some aspects of preference strength.

3. **Include soft attributes like 'manufacturability' or not?** Many of the benefit flows have multiple attributes, some soft and others hard. For example, the value of "Exploration Systems" is defined by quality, cost, timeliness, etc. The DoDAF captures 'soft' stakeholder expectations in the evaluation of an architecture. The difficulty with soft expectations is that they require implicit tradeoffs – if one architecture is superior on manufacturability, but the other is superior on extensibility, the eventual decision will express the architect's mental model of uncertain costs savings from manufacturing against the future benefit from an extensible design.

The tradeoff here is on human input – some of the decisions above rely on human input to evaluate each architecture. Human input may produce a more realistic decision process, but is more difficult to make rigorous. Given the prior history of the System Architecture group at MIT in executable architectures, and the goal of this section to define sensitivity to benefit delivery (which is much easier numerically), my decision was to pursue a cardinal approach, using realistic quantities, and only incorporating attributes which can be related back to an architecture variable. That being said, the focus on the evaluation of this method will therefore have to question the realism of this numerical approach relative to traditional ordinal approaches.

The approach taken here is to define 'proximate metrics', which represent the information that some architectures have a higher likelihood of producing a given output. This higher likelihood could arise out of greater re-planning capability, robustness of the equipment to different scenarios, or a number of other factors. The defining characteristic of these measures is that they don't need to assume needs are independent – one architecture variable can define the satisfaction of several needs.

A preliminary set of proximate metrics was originally developed by Catanzaro, Loureiro and Crawley. These are modified and expanded for the purpose of the case study in the next section. The desirable qualities for these metrics, as well as the meaning of 'real numbers' becomes more clear as these metrics are outlined.

One final note on the framework, before the delving into the details. I made a decision to use an architecture model without constraints, for simplicity. Architecture variables are defined, but it is assumed that any combination of variables yields a feasible architecture. Furthermore, no cost models or physical models are included in the architecture, which means that we can only rank architectures on benefit. As the cost is undefined, so is the value (where value is defined as benefit at cost).

Hypothesis
Architectures will produce different ranges of benefit for different benefit flows

Therefore, in order to investigate the hypothesis of whether architecture can be differentiated by benefit, I examine the spread of benefit produced by the defined architecture space. If the variability is uniform across benefit flows, the hypothesis will be rejected. If the variability is diverse across benefit flows, we will then have to question whether the chosen inputs and method were appropriate and realistic – if so, then we can accept the hypothesis.

5.2. Architecture Test Case

5.2.1. Choice of Variables

For the architecture test case, I chose six variables to define the architecture for a lunar campaign. These were not intended to span a full architecture space, but rather to define enough of a space to allow for the possibility of benefit differentiation. The six variables chosen were:

1. Heavy Lifter Launch Capability : The LEO injection mass (in MT) capability of the heavy lift launch vehicle.

2. Global Access : Whether or not the architecture caries a requirement to be able to land anywhere on the moon. While all landing sites are accessible on entry, the propulsive cost / time required to perform ascent varies between landing latitudes.

3. Crew Size : The number of crew members landed on the moon.

4. Duration of Stay : The number of days the crew is on the lunar surface, during a sortie mission. For a campaign schedule with varying sortie durations, the average duration would be used.

5. Science Mass : The cargo mass in kilograms dedicated to science instruments per sortie mission. This does not include rover or spacesuit mass. It is recognized that the actual boundary between science systems and the remainder of the vehicle will be fuzzy (for example, in the case where an instrument draws its power from the lander, does one consider the fractional battery use as science mass?), but at the current level of abstraction, this is a reasonable approximation

6. Rover Range : The one day maximum distance from the base that the rover can drive, including battery considerations and estimated part lifetimes. Note that the total distance traveled by the rover on a straight out-and-back mission would be double the Rover Range, as I have defined it.

Using these 6 variables, I first took a holistic look at the model, and asked which value flows we would expect the variables to affect. A tree diagram of those connections is shown in the figure below.

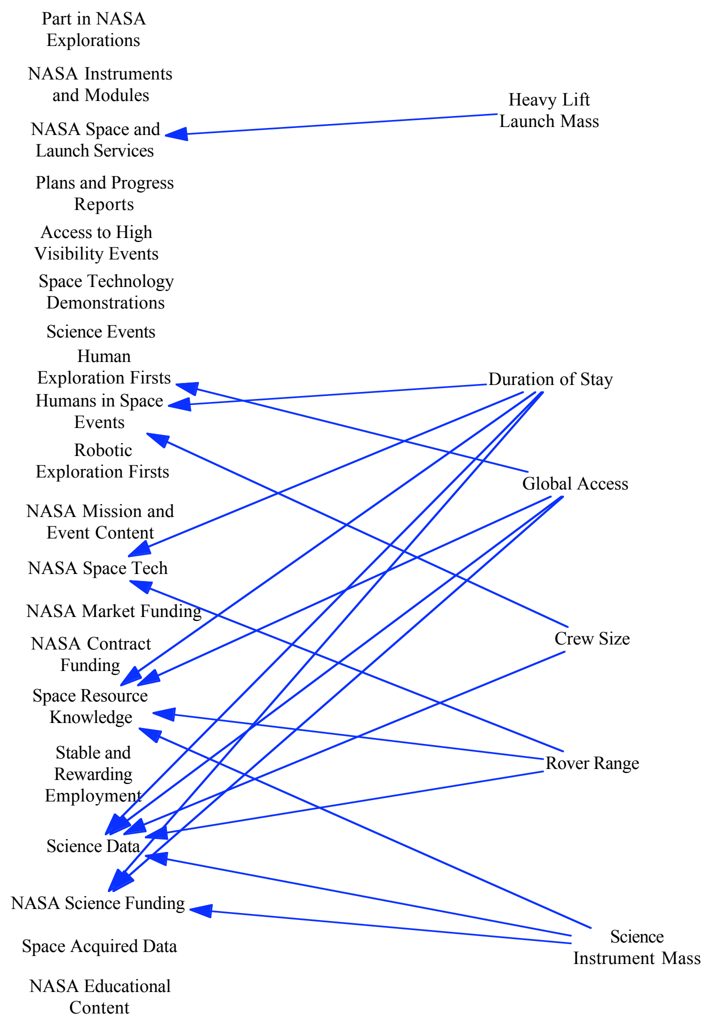


Figure 54 Connectivity of Architecture Variables (at right) To NASA Output Value Flows (at left)

Note that the architecture variables do not span the space of network flows. Only 7 / 21 possible flows are affected by the test architecture variables. Observe that NASA's output flows fall into three categories: Architecturally-determined Flows, Schedule-determined Flows, and Organizational Decisions. For example, NASA's ability to provide Plans and Progress Reports is primarily driven by the schedule set for the campaign, whereas the amount of Educational Material is almost purely an organizational decision, made largely irrespective of the architecture. Of the 21 flows identified, I label 16 as Architecturally-determined Flows, implying that 1/4 of the value space will not discriminate between architectures.

The 5 flows which I postulate will not be affected by the architecture are:

- Stable and Rewarding Employment
- Protection against claims of sovereignty over planetary bodies by other nations
- NASA Educational Content
- NASA Instruments and Modules to International Partners
- Plans and Progress Reports

Principle
Not all benefit flows will differentiate between architectures – some types of benefit will be produced regardless of which architecture is chosen.

The proximate metrics outlined in the following section will define how widely the remaining 3/4 do discriminate.

The ranges for the architecture variables are shown in the table below. These values were chosen to represent a reasonable design space for a lunar outpost mission.

Table 10 Minimum and Maximum Test Values For Architecture Variables

	Min	Max
Heavy Lift Launch Capability	67MT	130MT
Global Access?	Equatorial	Global
Crew Size	2	6
Duration of Stay	5 days	30 days
Science Mass	100 kg	1000 kg
Rover Range	10 km	100 km

5.2.2. Proximate Metrics

Proximate metrics are used to connect the architecture variables to the value flow delivered. I first highlight some of the desirable qualities of such metrics, and then describe the metrics that were created.

The function of a metric is to bring together a number of different types of information into a single value, on which useful decisions can be made. Given that there are many possible ways to aggregate or layer data from a mission, how should we determine which proximate metrics to create? The answer arises out of the value model –

a proximate metric is required for each NASA output. Therefore, the rigor with which the value model was created allosws us to determine the number and description of the proximate metrics.

> **Principle**
> The outputs of the organization in a value network model define the space of proximate metrics required for architecture evaluation

This does not solve the problem entirely, in that it does not create specify how proximate metrics are defined. In the long term, good metrics have to be evaluated by their ability to correlate indicator variables to behavior. There is significant work on this for science satellites, particularly for telescopes[58,59]. However, given that there are few metrics for exploration, we can make some reasonable assumptions in order to begin to design these metrics.

For reference, I have included Cook's description of the function of performance measures below [Cook, p.141]:

1. Track sources of competitiveness
2. Encourage improvements that benefit the enterprise, its customers, and society.
3. Benchmark against your major competitor
4. The sum of local measures should equal the performance of the enterprise.
5. Be in harmony with the organizational structure.

In order to facilitate decision making, I enforce that each metric should condense the inputs to a single value, for ease of later computation. While I do intend to propagate this scheme through all values flows in the model, and I have constrained each flow to be a uni-dimensional quantity, I don't intend to further condense multiple flows into aggregate 'Total Stakeholder Satisfaction' values. The intent is that the architect's decision space should act at the same level of complexity as the original value flow model.

In order to examine different ways of combining these different types of information, I first delineate between additive versus multiplicative metrics. Additive metrics suggest the component inputs are all tradable, or in other words, each have the same potential to deliver value. Product metrics, particularly normalized ones (defined on [0,1]), suggests co-dependency of components, in that the product cannot be maximized unless all components are active. Product metrics have the unique quantity that doubling a component's contribution doubles the output. Both additive and multiplicative metrics are employed below, depending on the situation.

Finally, with a view to enabling 'useful' decisions, I submit that some form of stakeholder input is required. Ideally, the metric used should coincide with a physical value of interest to the stakeholder, on which the stakeholder can then offer an anchored opinion of benefit. For example, for NASA Launch and Space Services, the key concern for receiving parties is the launch mass the lifter is capable of. I use the concept of the utility curve to encapsulate stakeholder input. The utility curve maps the input value (as the independent variable) to the perceived value to the stakeholder. Monotonically increasing utility curves are used, defined by the 0%, 10%, 90% and 100% value levels, with linear interpolation in between.

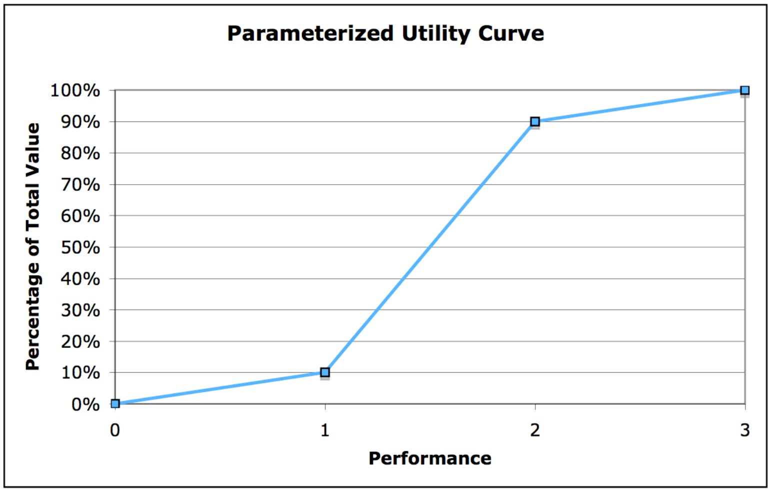


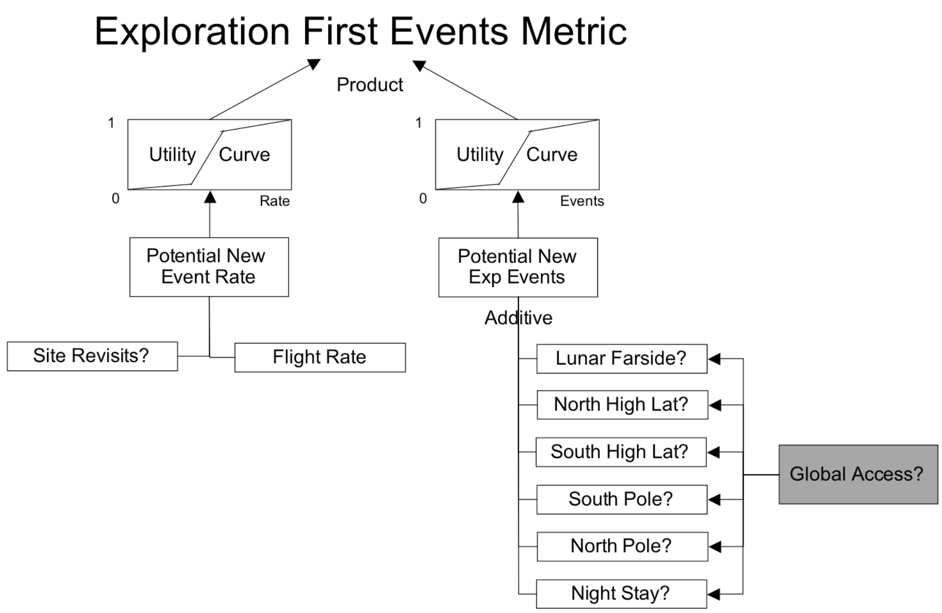
Figure 55 Example Of A Parameterized Utility Curve

In this manner, I can represent value delivery with clear thresholds (such as Humans in Space Events, which saturate media coverage above certain frequencies of events) by defining the 100% value mark at the threshold, as well as representing open-ended value delivery flows (such as ‘Science Data’), where a marginal increase will continue to deliver marginal value, by setting the 90% or 100% levels to unachievable levels. Given that the purpose here is to enable relative comparisons between architectures, I am more concerned that the metric captures the full space of input ranges (and therefore all architecture value movements with relevant value impacts are captured) than with defining the precise upper bound at which a stakeholder can be said to be 100% satisfied with the value delivered.

Two examples are used below to illustrate the methodology, namely the metrics for Human Exploration First Events and for Science Data. Architecture variables are shown at the bottom of the metric diagrams in grey.

The **Exploration First Events** metric captures two basic attributes, the number of exploration events and the frequency. Given that the test architecture chosen is limited to the sortie phase, I used new destinations and night stays as simple proxies for exploration events. The number of events is then passed through a utility curve, which represents the number of events within a campaign which the public would perceive as 'exploration', before the mission type would become routinized to the extent that further missions would represent 'Humans in Space Events', rather than 'Exploration First Events'. The 90% threshold for this curve was set at 3 events for this phase of the campaign. The campaign's ability to provide these events depends on the global access architecture variable, as well as the duration variable. The events are totaled, and then passed through the utility curve. I calculate the frequency of new destination visits based on a flight rate and the extent to which the architecture builds in site revisit requirements / assumptions. Given that neither of these is trades in our test architecture space, both are set to reasonable maximum values. The frequency and quantity aspects of this metric are modeled as a product, in that flight frequency and the capability to go to new places are required to produce Exploration Firsts.

Figure 56 Exploration Firsts Events Metric



The **Science Data** metric abstracts across all types of data (visual survey, sample return, imaging, etc.) by capturing a Quality and a Quantity aspect. I make the simplifying assumption that the Quantity of Data is proportional to the available crew science hours, which in turn is influenced by crew number and mission duration. The bounds on Quantity of Data are determined using a 'operating hours per instrument' guideline, where the 90% threshold is set at 10h/instrument (well in excess of the Apollo computed average of 1.23h/experiment, assuming a 60% science & experiment time fraction [60,61]). This calculation does not yet incorporate planned autonomous operation - for example, some of the Apollo experiments operated for 45h or longer. Quality of data is a multiplicative composition of the accessible area (defined by rover range), rover speed (which enhances choice and flexibility in the areas to study), diversity of landing sites (defined by the Global Access variable), and Mass Per Science Instrument (MPI). Each of these components has an individual utility curve, given that a generalized metric for the quality of science data (like Signal to Noise Ratio) is not available. For example, the MPI 90% value was set to 100kg, double the Apollo 16 average of 49kg per instrument. The Quality and Quantity metrics are normalized on [0,1], and then multiplied to yield the Science Data metric final value.

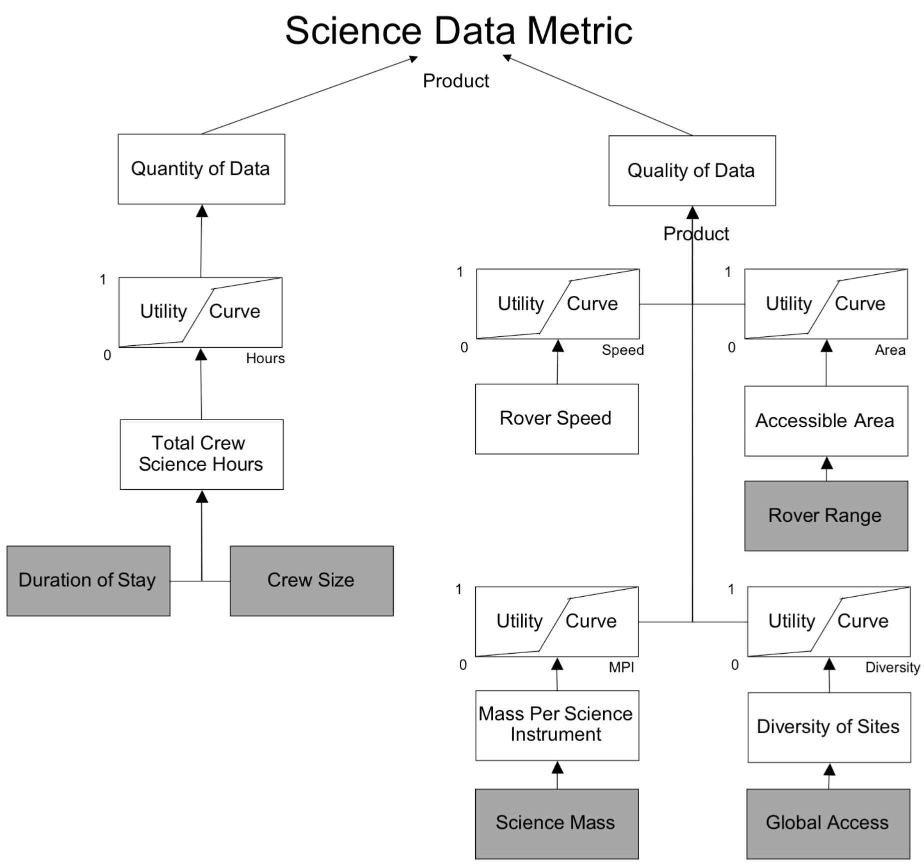


Figure 57 Science Data Metric

The remaining proximate metrics were developed in a similar manner, each aligned to a particular value flow. Therefore, I have a [0,1] completion value for each of the NASA output value flows. The next section explains how the state of stakeholder internal assets are calculated using our network model.

Note that I have satisfied Cook's performance measures guidelines 2 and 4 only. Guidelines 1 and 3 (track sources of competitiveness, benchmark against competitors) is not relevant in a public model. Guideline 5 (relation to organizational structure) will be covered in Section 5.3 Architecting in the Real World.

5.2.3. Propagation in the Benefit Model

The benefit model already contains all of the connections necessary to trace a path from a NASA output to all of the stakeholders impacted, but it does not yet contain equations for calculating flows or internal assets as a function of NASA outputs.

Predictably, I chose normalized scales for internal assets and flows, in order to facilitate computation. Given that connectivity is already established by the network model, the only aspect that remains is to determine the relative weightings of the inputs.

For stock inputs, I use the Kano-Importance values as weights. I tested a set of weights that I created specifically, but I found that the difference between my decisions for weightings and those computed from the Kano-Importance were roughly equal to the error from differences between decision makers (on the order of 20%). Using the Kano-Importance data does introduce a significant new assumption: the weighting of inputs to a stock is assumed to be the same as the weighting of those inputs to the stakeholder as a whole.

For flow inputs (which are the outputs of internal assets), I assigned my own values to the weightings of the internal assets. Given that the internal assets were created with the outputs in mind, the vast majority of outflows depend on only one stock. For those that depend on more than one stock, the weighting is typically an even distribution.

Given that we now have information, solving the system is the final step. The equations described above are initially formulated into a linear system of coupled equations of the form $AX = 0$, where X is a vector of all of the value flows and internal assets (including the known values for NASA's outputs), and A is a coefficient matrix containing the flow to stock and stock to flow mapping described above. This solution setup is shown graphically in the figure below.

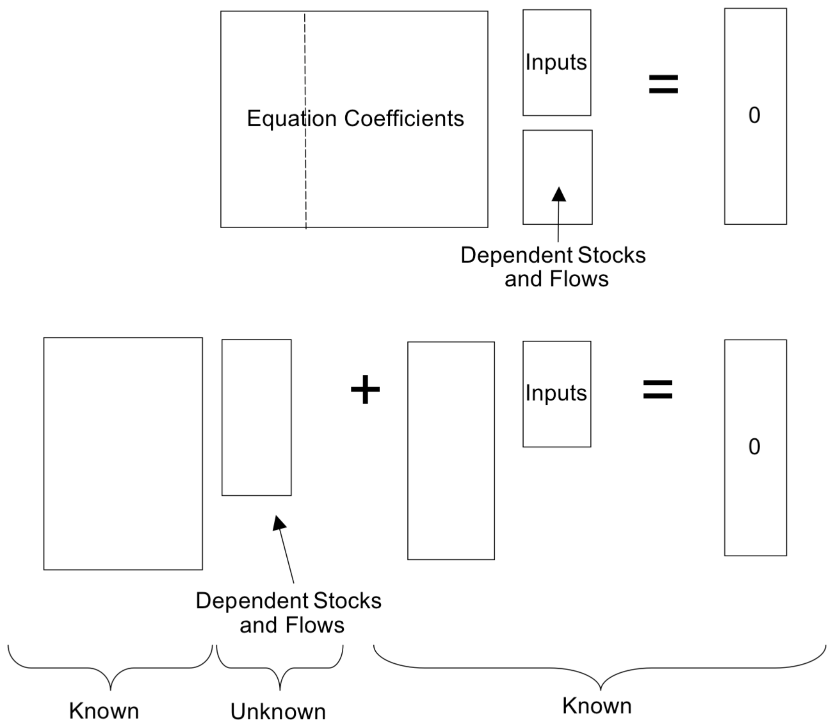


Figure 58 Solution Form For Link Values

5.2.4. Test Results

From the set of test architecture values, I am chiefly interested in how broadly they span the benefit space described. Identification of benefit flows that are insensitive to changes in architecture values sheds light on both prioritization in the design process, as well as opportunities for greater stakeholder interaction. Given that I have not yet introduced budget or performance constraints, I do not select architectures at this stage – I merely examine the minimum and maximums of the value space.

The first test of our model is to ask how great a variation in NASA outputs it yields, shown in the diagram below.

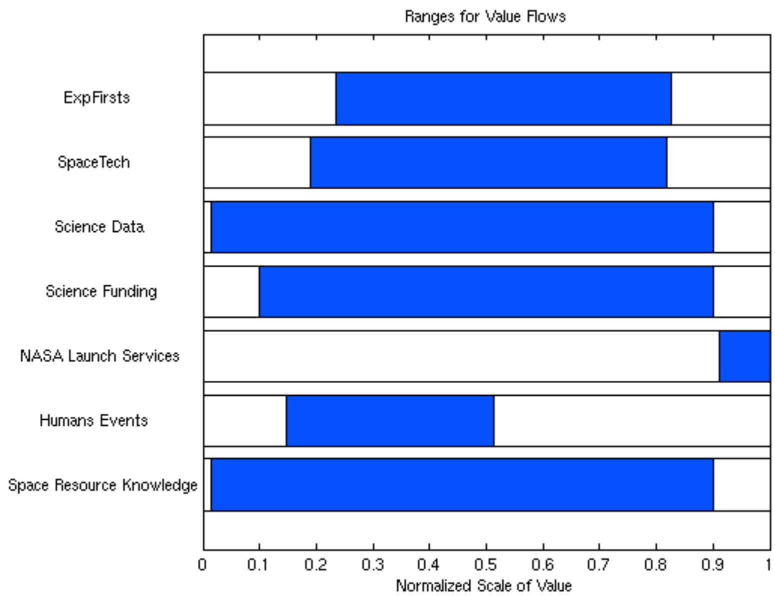
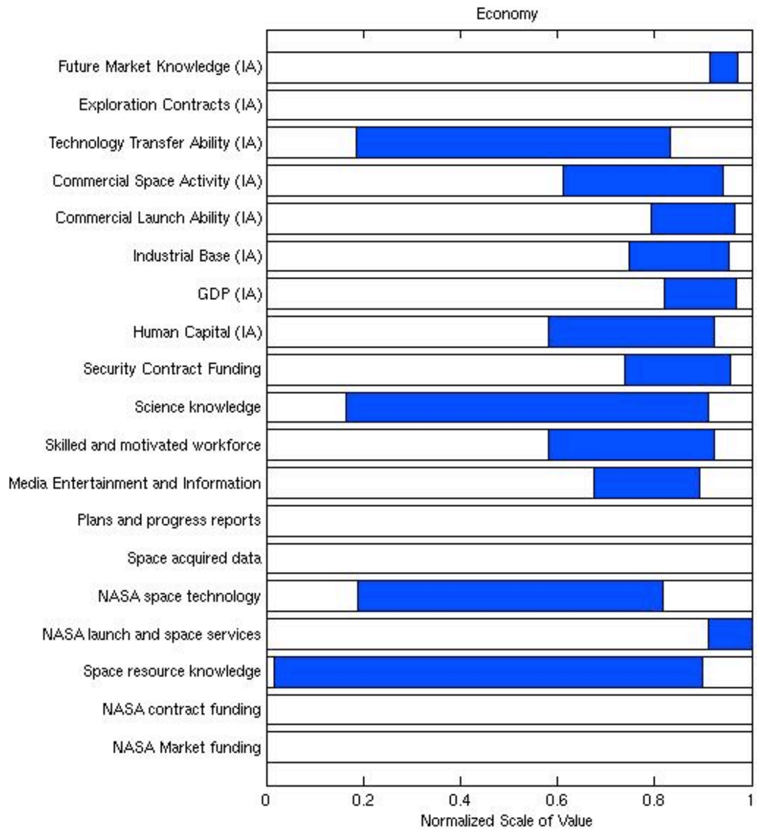
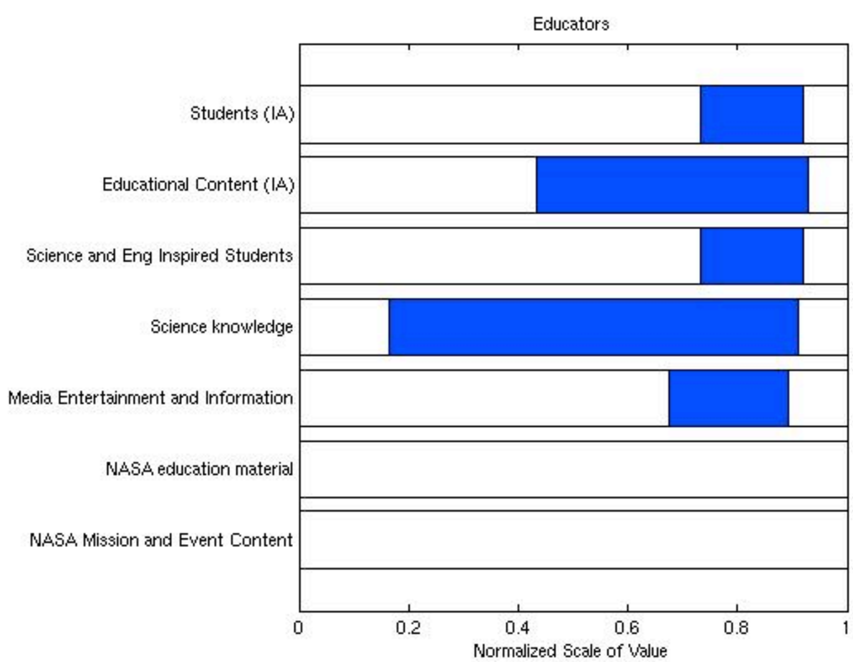


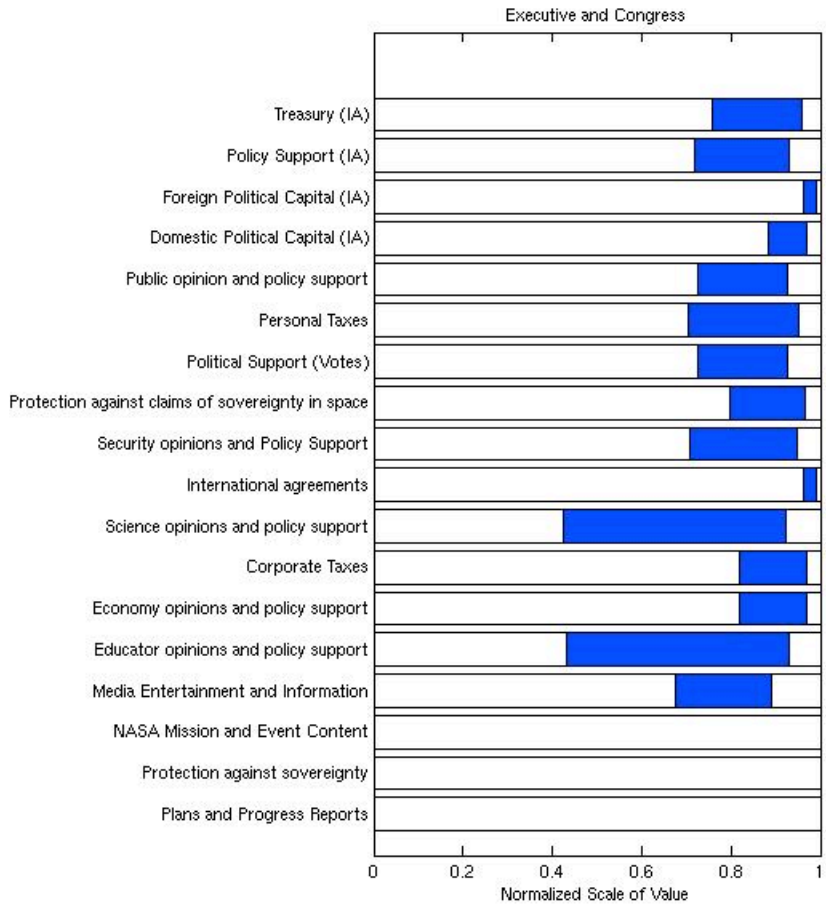
Figure 59 NASA Output Flow Ranges

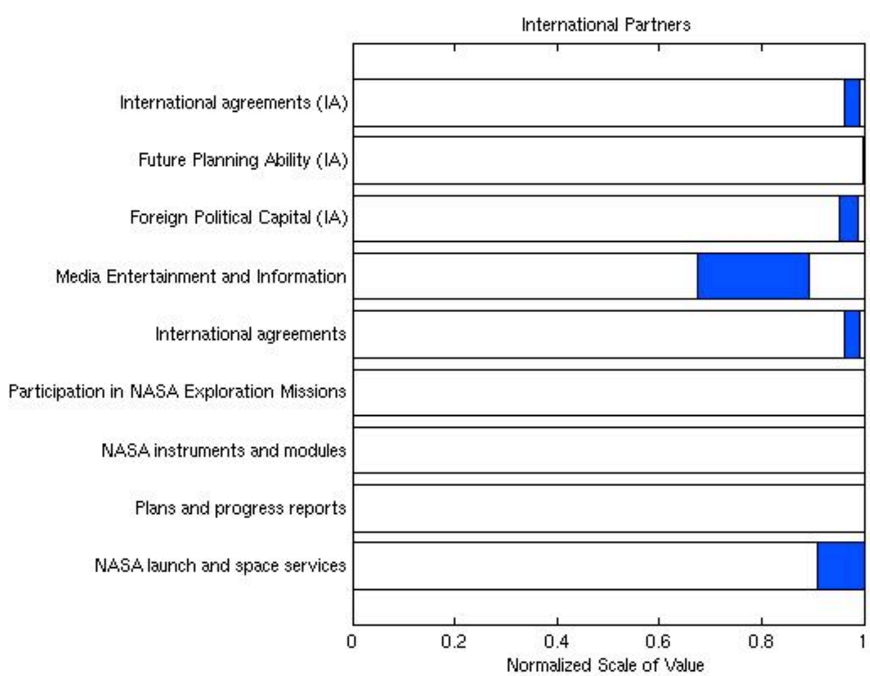
The test architecture ranges cover a fairly wide range of the benefit space defined, with the exception of NASA launch services. This is due to the construction of the utility curve, which assumes that a marginal increase in the maximum launch weight, over a Delta IV Heavy, would provide significant value, and doubling the security community's current launch mass would deliver 90% of the value. However, this only gets us to the lower end of the test architecture range. Human in Space Events shows a fairly narrow range as well, primarily because the duration component of the metric, which postulates that the public's perception of a 'long' stay in space is on the order of a year, which is well outside the architecture space.

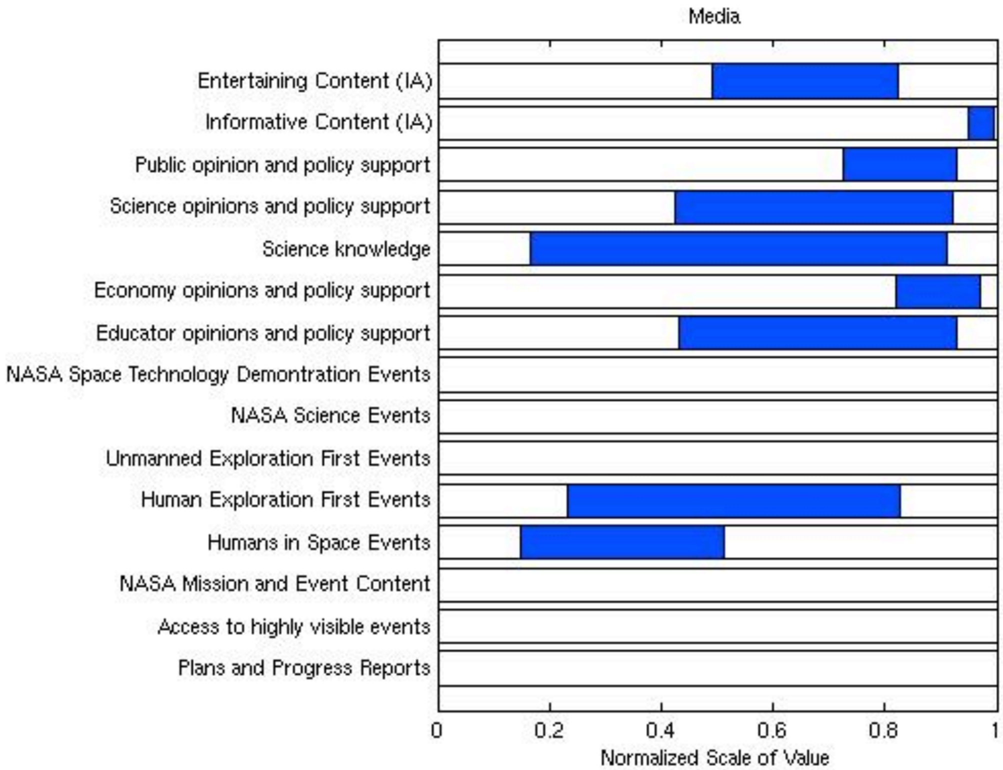
After propagating these 7 NASA Outputs through the model, and assuming the other 14/21 outputs are equal to 1, we see the following behavior. Note that a blank bar indicates that the flow or internal asset contains only the value one, not zero, because we assumed all other flows are at their maximums. Internal assets are indicated with "(IA)".

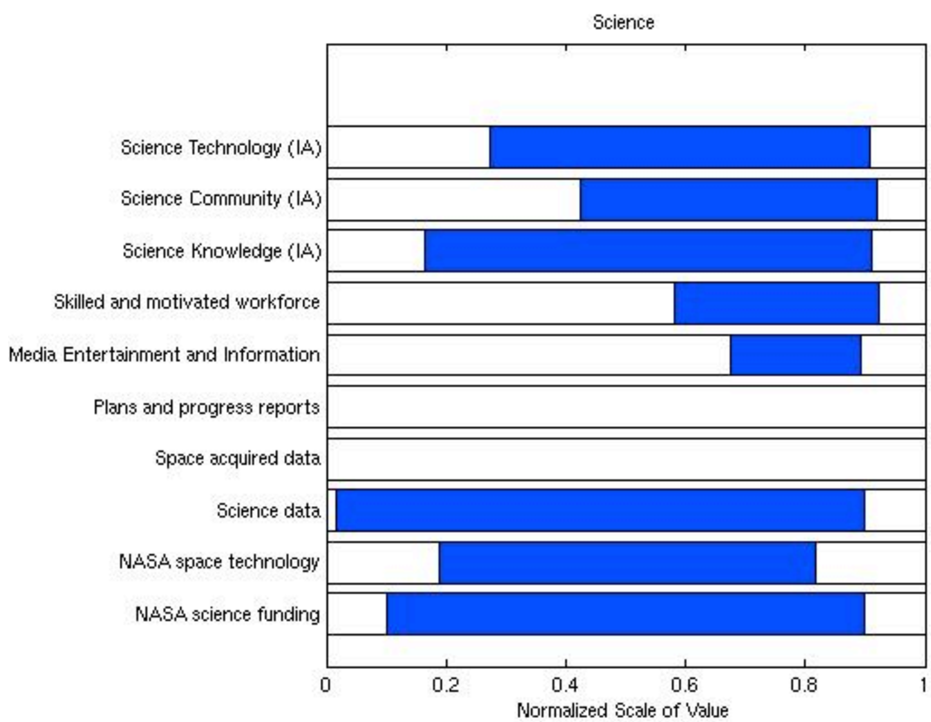

Economy
Future Market Knowledge (IA)
Exploration Contracts (IA)
Technology Transfer Ability (IA)
Commercial Space Activity (IA)
Commercial Launch Ability (IA)
Industrial Base (IA)
GDP (IA)
Human Capital (IA)
Security Contract Funding
Science knowledge
Skilled and motivated workforce
Media Entertainment and Information
Plans and progress reports
Space acquired data
NASA space technology
NASA launch and space services
Space resource knowledge
NASA contract funding
NASA Market funding
0
0.2
0.4
0.6
0.8
1
Normalized Scale of Value

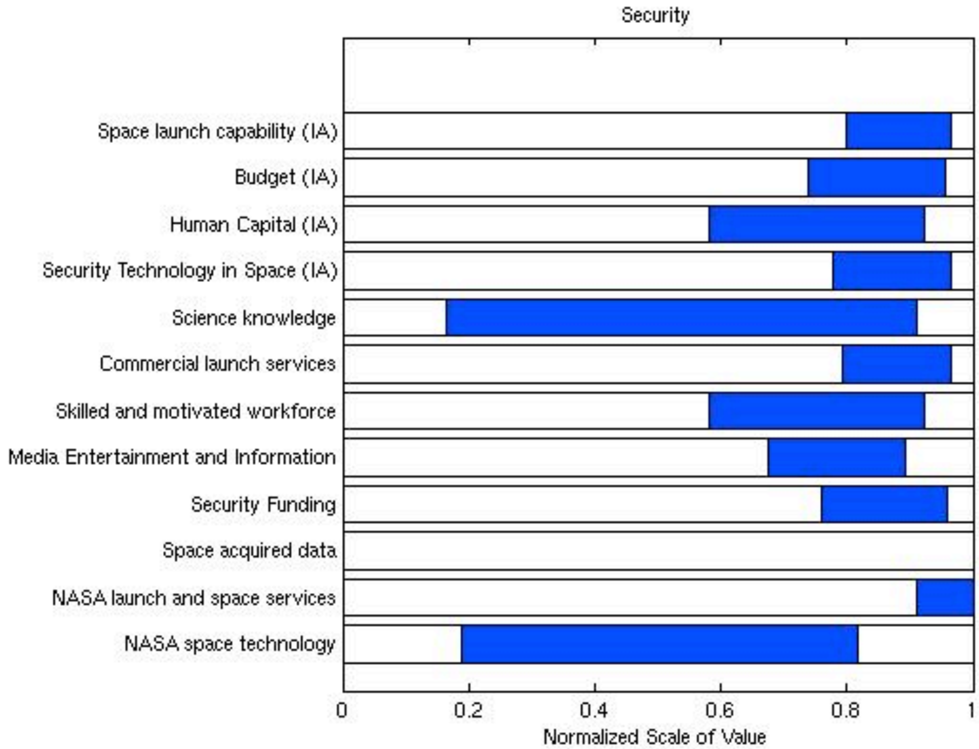

Educators
Students (IA)
Educational Content (IA)
Science and Eng Inspired Students
Science knowledge
Media Entertainment and Information
NASA education material
NASA Mission and Event Content
0
0.2
0.4
0.6
0.8
1
Normalized Scale of Value

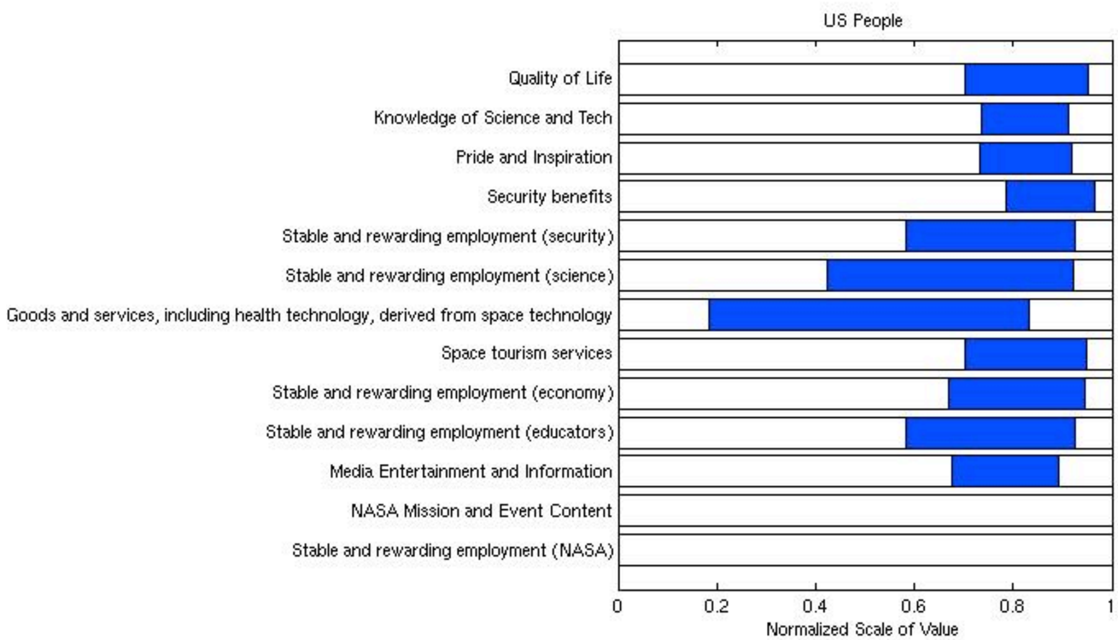

Executive and Congress
Treasury (IA)
Policy Support (IA)
Foreign Political Capital (IA)
Domestic Political Capital (IA)
Public opinion and policy support
Personal Taxes
Political Support (Votes)
Protection against claims of sovereignty in space
Security opinions and Policy Support
International agreements
Science opinions and policy support
Corporate Taxes
Economy opinions and policy support
Educator opinions and policy support
Media Entertainment and Information
NASA Mission and Event Content
Protection against sovereignty
Plans and Progress Reports
0
0.2
0.4
0.6
0.8
1
Normalized Scale of Value


International Partners
International agreements (IA)
Future Planning Ability (IA)
Foreign Political Capital (IA)
Media Entertainment and Information
International agreements
Participation in NASA Exploration Missions
NASA instruments and modules
Plans and progress reports
NASA launch and space services
0
0.2
0.4
0.6
0.8
1
Normalized Scale of Value


Media
Entertaining Content (IA)
Informative Content (IA)
Public opinion and policy support
Science opinions and policy support
Science knowledge
Economy opinions and policy support
Educator opinions and policy support
NASA Space Technology Demontration Events
NASA Science Events
Unmanned Exploration First Events
Human Exploration First Events
Humans in Space Events
NASA Mission and Event Content
Access to highly visible events
Plans and Progress Reports
0
0.2
0.4
0.6
0.8
1
Normalized Scale of Value


Science
Science Technology (IA)
Science Community (IA)
Science Knowledge (IA)
Skilled and motivated workforce
Media Entertainment and Information
Plans and progress reports
Space acquired data
Science data
NASA space technology
NASA science funding
0
0.2
0.4
0.6
0.8
1
Normalized Scale of Value


Security
Space launch capability (IA)
Budget (IA)
Human Capital (IA)
Security Technology in Space (IA)
Science knowledge
Commercial launch services
Skilled and motivated workforce
Media Entertainment and Information
Security Funding
Space acquired data
NASA launch and space services
NASA space technology
0
0.2
0.4
0.6
0.8
1
Normalized Scale of Value


US People
Quality of Life
Knowledge of Science and Tech
Pride and Inspiration
Security benefits
Stable and rewarding employment (security)
Stable and rewarding employment (science)
Goods and services, including health technology, derived from space technology
Space tourism services
Stable and rewarding employment (economy)
Stable and rewarding employment (educators)
Media Entertainment and Information
NASA Mission and Event Content
Stable and rewarding employment (NASA)
0
0.2
0.4
0.6
0.8
1
Normalized Scale of Value

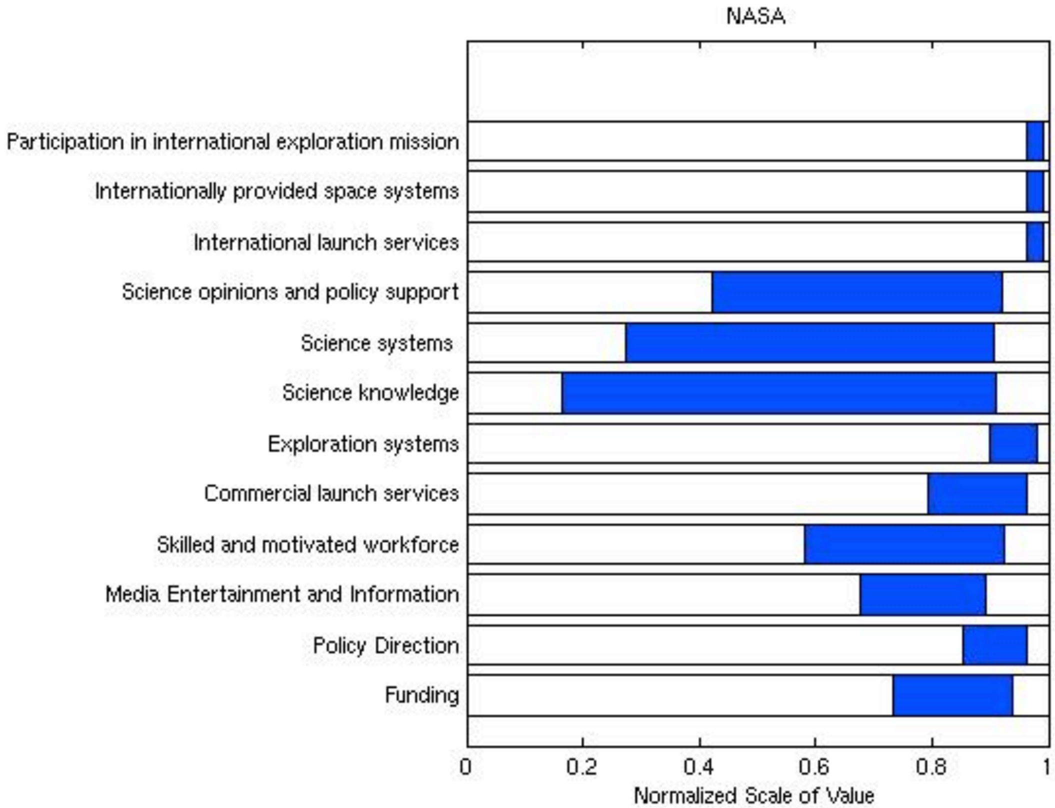


Figure 60 Value Ranges For Stakeholder Inputs And Internal Assets

The model demonstrates that several flows are insensitive to the architectural space we have established. For example, international agreements vary very little, as does the Economy's ability to provide Exploration Systems. We also see large ranges over some flows, notably Science Knowledge and Goods and Services Derived From Space Technology (from the Economy to the US People).

With a view to capturing the extent to which different stakeholder see a wide range of value delivery, I computed the average range over which their input flows varied. This is not intended as a measure of stakeholder satisfaction, because it does not apply a weighting to different inputs.

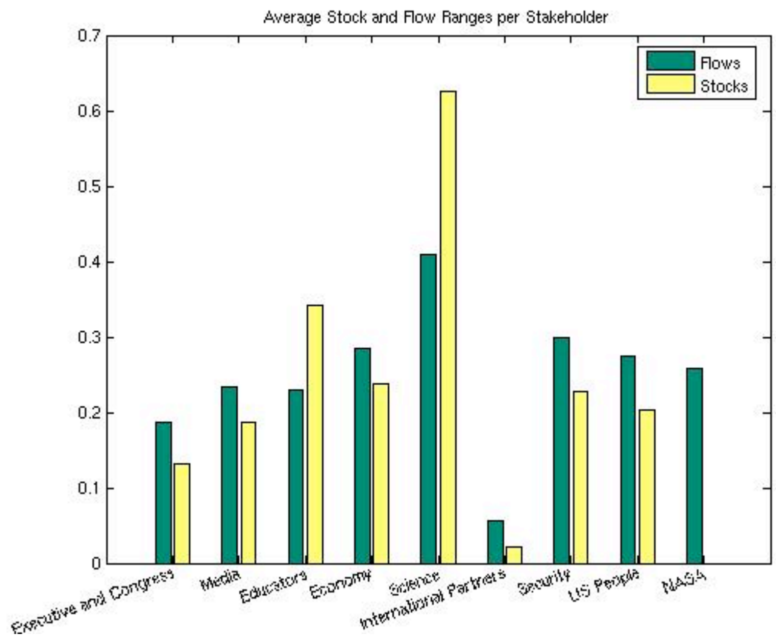


Figure 61 Average Value Ranges Across Stakeholders

Science internal assets show the greatest variation by far. Given the selection of a subset of value flows that I have chosen, it is reasonable to wonder whether I have applied some selection bias, and in doing so, have illustrated more of the decisions relevant to science but not those relevant to other flows. While this is a legitimate concern, an examination of the remaining architecturally significant flows suggest that we are unlikely to see a radically different picture, because the remaining flows also focus on science and the economy:

- Participation in NASA Exploration
- NASA Contract Funding
- NASA Market Funding
- Unmanned Exploration First Events
- Space Technology Demonstration Events
- NASA Science Events
- Space Acquired Data

From a basic logic perspective, we might reasonably expect that the most technical stakeholder is likely to be most sensitive to architectural decisions. However, if we judged the output to be under-representing the sensitivity of non-science flows, there are several avenues of recourse:

1. Verify utility curves for the corresponding NASA outputs, particularly if there is a unique mapping from the output the flow in question. One could also examine the relative sensitivity of the metric to particular utility curves within that metric.

2. Examine the diversity of outputs contributing to the flow. If one output can compensate for the lack of a second output (additive rule), then an inverse correlation between the two metrics could cause the flow to remain constant.

Consider adjusting the number of links of different stakeholders. An under - representation of the connectivity of one flow to NASA's outputs would cause the flow to vary with a narrower set of outputs than appropriate, which may not be representative.

That being said, the hypothesis was broadly defined as demonstrating differentiation among architectures by benefit, which was achieved. I highlight *demonstrating*, because the input values to the model are notional, which implies that calibration of the specific sensitivity of different stakeholders would require survey data.

Hypothesis Confirmed
Architectures will produce different ranges of benefit for different benefit flows

What can we tell from this type of information?

Assuming for a moment that we could define the sensitivity of different flows to stakeholders accurately, the question becomes what use would it be? First, it would inform who should be allowed input to the design process – stakeholders who are insensitive to benefit should not have the opportunity to influence design decisions. Second, where decisions are taken in light of a stakeholder's sensitivity to a particular flow represents an opportunity to build buy-in with that stakeholder in response to a decision taken in their favor.

Adding constraints would be the next step in exploring this sensitivity. With a coupled model of benefit and cost, one could examine the relative change in sensitivity or priority between stakeholders necessary to cause a change in the best architecture. This would be a significantly more tangible outcome of a stakeholder sensitivity analysis.

Moreover, with constraints one could examine benefit for different architectures graphically, but where not all flows can be satisfied. The sample output produced below is one graphical representation, where flows are illustrated differently depending on their Kano category. The height of each flow is determined by its Kano-Importance value (read as the maximum utility), multiplied by a 'completion' factor determined from the proximate metrics. Must Haves are represented as negative, therefore at zero completion the bar has a maximum negative value, and for 100% completion, has a height of zero.

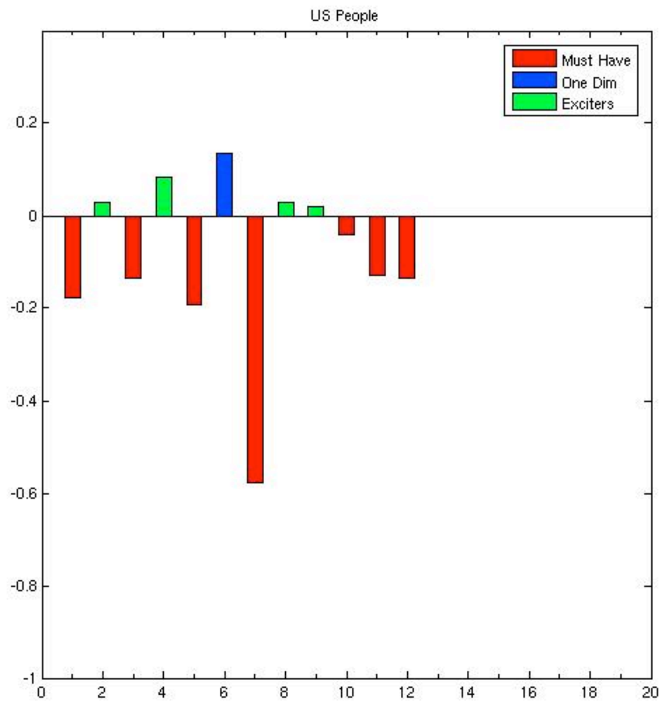


Figure 62 Notional Stakeholder Benefit Graph From A Particular Architecture

Additionally, one could sum these input flows at ratios defined by their Kano-Importance values to produce a per-stakeholder benefit graph as given below.

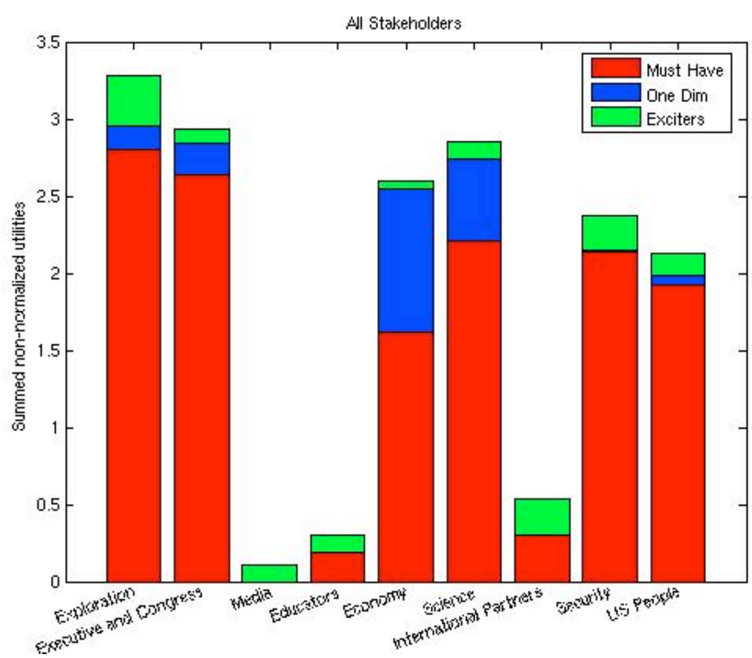


Figure 63 Notional Stakeholder Benefit Chart With Kano Breakdown Shown

5.3. Architecting in the Real World

In theory, there is no difference between theory and practice.
But, in practice, there is.

- Yogi Berra

The approach thus far has been to look for quantitative methods by which one can encode and analyze information on stakeholders as relates to architecture selection. Given the relative complexity and novelty of these methods, efforts were made to keep the inputs simple. This required a number of assumptions, in terms of the inputs, the dynamics of the model, and the utility of the outputs. The function of this section is to analyze a number of additional considerations, many of them relaxations of the original assumptions, to determine the extensibility of the model, the potential impact of the current output, and most importantly, the shortcomings.

5.3.1. On Inputs

Thus far, I have used very high level needs. In reality though, needs exist at many different levels of detail. For example, the needs of International Partners may be very granular, such as the allowable vibration through an interfaces, but still relate to fundamental architecture variables (like staging and landing area choice). By contrast, the needs of the US Public may be very high level, as shown in the current model.

This raises several questions:

1. ***Should we attempt to build a model into sufficient detail that the satisfaction of all needs can be computed?***

The real difficulty is that value for different stakeholders is based on different aspects of the design. For the overall need to explore the moon, the needs of different stakeholders act at different points on the system. The contractor may care if the Specific System Form includes solid rocket motors, while the scientists operating an experiment may care about attributes of the operating process like a continuous uplink capability. I have represented this in the diagram below by showing that value derives from different levels of decomposition of the OPM. In reality, these OPMs are really nested, so I could actually draw a separate OPM for each granular need.

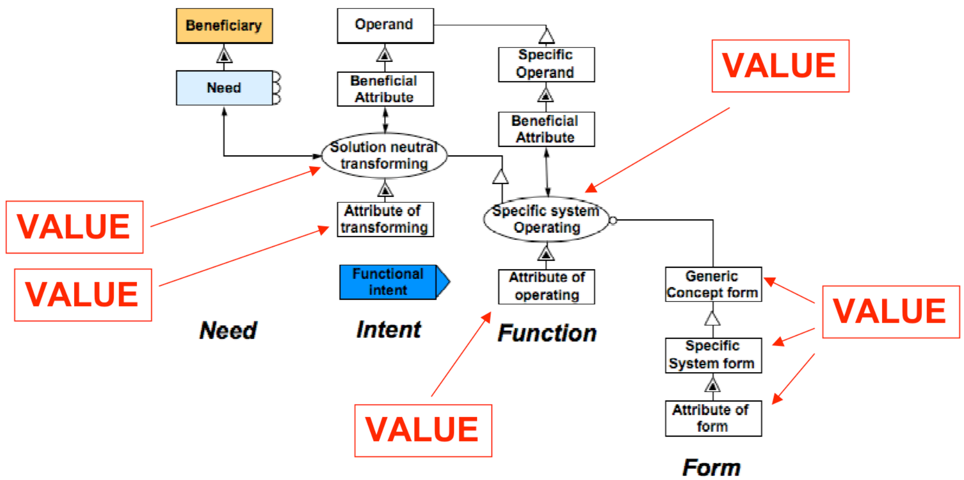


Figure 64 OPM of Needs Decomposition With Potential Value Attributes Shown (Adopted From Crawley ESD.34 Course Notes)

The trade-off that has to happen here is the depth of modeling vs. time to make an architecture decision. The interfaces in the system also have a significant impact – a system with clean interfaces and separate forms for each function will be significantly less complex to model in more detail that would a system where a handful of forms serve multiple functions.

2. *Should low level needs be traceable to high level needs?*

There are a number of tensions here. First, zooming needs (specifying attributes) can reduce architecture options, but could help define more specifically what stakeholders are concerned with. Second, zooming needs out to significant detail and defining a mapping can obscure the satisfaction of the original high level need, incentivizing a 'letter of the law' approach over the 'spirit of the law'. Third, as suggested above, some needs may naturally lie at different levels of detail – creating high level needs to help roll up all needs may obscure the meaning of the original need. Finally, needs are purposefully expressed from the perspective of the stakeholder, and it may therefore be difficult to define levels of detail across needs. This can be done at the expense of tying needs more closely to a specific architecture.

Rather than focusing on the traceability of needs, I submit that evaluating satisfaction of needs (whether by verification and validation, or by using proximate metrics) is the more important aspect to focus on. If creating a tree of needs aids if the evaluation, then it should be entertained as a possibility. Otherwise, it may create more complexity than required.

3. What are the implications of building a benefit model at more detail?

As mentioned in Section 3.1, the number of stakeholders chosen defined the level of abstraction for the model. If we had chosen a greater number of stakeholders, we would likely have expanded the Science and Security groups to specific institutions, and also defined the sectors of the economy and the people relevant to the network. This would result in several challenges:

1. **The temptation to sketch different attributes of flows.** For example, the quality, timeliness, and cost of individual exploration systems. Each of these qualities needs a model to determine fluctuation in the attribute, based on changes in input, which would scale the size of the model dramatically.

2. **Duplication of paths.** As we define more actors, it becomes possible to use several actors to perform the same function. For example, we could go define different news agencies, each of which produces media content. Unless the type of content differs significantly, this doesn't help us represent more information about the strongest loops, because there are now more loops in the model of equal strength.

3. **Tendency towards an event driven model.** There is a point beyond which detail cannot be increased without naming specific actors. Taking contractors as an example, different architectures will favor specific contractors, which implies the architecture will have to capture elements of form in sufficient detail to differentiate between contractors. I remain concerned about the validity of modeling benefit in this detail, given the uncertainty involved.

4. **Potentially easier valuation of inputs.** The more specific the input, one would expect it would become easier to define the benefit, given that the receiver can compare specific instantiations from the past, and there is less averaging across heterogeneous groups (assuming smaller stakeholder groups are more homogeneous).

5. **Longer paths through the network.** The modeler would have to define more specific procedures for managing the level of detail, to ensure that less detailed areas did not create a bias towards shorter loops.

This discussion tends somewhat towards the negative side of creating a model with more detail. Part of this hesitation stems from the unknown, given that it has not yet been attempted. However, I am more concerned that it would shift focus away from the softer considerations of benefit, and introduce a false confidence in details. The reality is that many of these tradeoffs are difficult to make, and the dynamics of different options involve significant human action and decisions. While attempts have been made to linearize these behaviors into deterministic input-output functions, the emphasis needs to be on the feedback loops that really create benefit, many of which are observable from a given architecture, but cannot necessarily be decomposed into atomistic attributes. Therefore, the human ability to conceptualize the level of detail in the model is an important component of the success of the model.

Principle
The human ability to conceptualize the level of detail in a benefit model is an important component of success when attributes of the benefit are observable but not decomposable.

4. What if needs change?

There are a couple mechanisms by which needs could change. The baseline performance expectation for a flow could change, which would shift the Kano curves. The stakeholder perception of the importance of a need could shift, relative to their other inputs. Or the stakeholder could define new flows that represent new needs. The section below tackles these problems in order. Note first though that the framework here is primarily deterministic, as compared with Catanzaro's stochastic method, for reasons the outlined in Section 2.3. The reader is directed to Catanzaro's thesis for a more complete exploration of the survey problem and non-homogenous stakeholder expectations.

Change in the baseline performance expectation occur routinely in consumer products, as technology disperses through the market, transitioning from Exciter to Must Have typically. Where the performance of the attribute encounters physical limitations, or saturates satisfaction at higher levels of performance, the coupling between performance expectations and changes in Kano category will be accentuated. In space systems, where product cycles are measured in single digits, one might expect performance expectations to vary less over time. Certainly competition from other nations and private ventures will also shift expectations. Fundamentally though, this is easily accommodated by re-computing the model with new values.

Change in stakeholder perception of a need could be the result of re-aligned internal objectives or market entry of a competitor with a substitute service for that need. Assessing the likelihood of internal changes can be divided into uncertainty around needs and conflicts around needs. Uncertainty in the priority of needs could potentially be examined by performing pairwise comparisons of needs and analyzing the priorities for logical conflicts. One might also see hints of this behavior from centrally clustered Kano-Importance data (regression to the mean), or negative correlation between Kano categories and Importance. Looking for conflict within a stakeholder group is an easier task, accomplished by examining the variation in rankings or scores of the same needs across the population. Higher rates of conflict might indicate a higher probability of change in the future.

There is unfortunately no direct analysis that can be performed to determine how likely a stakeholder is to suggest new needs, because new needs are by definition exogenous. One could certainly examine the stakeholder's past requirements definition history, as well as the quality of the needs-identification process. One might expect this to be a bigger problem for individuals rather than groups – the hope is that surveying groups captures a bigger set of possible priorities, which can then be fed back to all individual members for ranking.

The question that arises here is should uncertain or changeable needs be treated differently in terms of potential benefit? The simplest treatment would use differences in group survey data to define possible ranges for individual link values. Running the minimum, maximum, and average cases would enable one to produce error bars on the stakeholder participation in important loops, as well as the distribution of input and output flows from NASA. One could also defined variation in rank of loops as a metric to indicate how changes in link value impact the model output, as discussed for link sensitivity analysis.

The other mechanism for addressing uncertainty in strong loops would be to establish a tradeoff between uncertainty and rank, such that loops with a higher number of links with variance, or loops with links with greater uncertainty would appear lower on the ranked list. Given that the purpose of strong loops is to identify chains where one can propagate influence, less certain links would certainly be less useful in causing change. I would be hesitant to apply such an 'uncertainty weighting', simply because it would imply that individual link values are already calibrated against observed behavior. However, uncertainty and change are central themes in system architecture, and one could certainly entertain a discussion of robustness vs. optimality of benefit in different uncertainty climates.

Needs Framework

With a view to enabling future pre-processing of needs, I propose the following framework, which divides needs into four categories of interaction.

1) Common needs
2) Synergistic needs
3) Conflicting needs
4) Orthogonal needs

Common needs are the easiest to recognize – two stakeholders have the same need. For example, both NASA and Security have a need for a skilled workforce.

Synergistic needs result when the satisfaction of one need acts to help satisfy another, or when the same action acts to satisfy different needs. Synergistic needs often result when two stakeholders are connected to each other – for example, satisfying the media's need for 'Access to high visibility events' helps satisfy the US People's need for 'Entertainment and Information'. Another example of synergistic needs occurs when launching a spacecraft satisfies both the Economic community's need for 'Contracts' as well as the Science community's need for 'Science Data'.

Conflicting needs are significantly more difficult to recognize, because they often result from an external constraint – such as the conflict between 'Gather science data' and 'Test new technology in space' under the constraint of fixed funding.

Orthogonal needs are needs that are not influence by the satisfaction of other needs – for example, we can say that the US People's need for goods and services derived from space technology is independent of their need for stable and rewarding employment. The reality is in fact that relatively few needs are actually orthogonal, as the satisfaction of a need by an architectural feature often has some implication for cost, schedule, performance or operational risk.

Using a coupled architecture-stakeholder model, one should be able to determine which needs are synergistic, conflicting, or orthogonal. Changing an individual architecture parameter at a time, one would expect the covariance of synergistic needs to be positive, the covariance of conflicting needs to be negative, and the covariance of orthogonal needs to be zero. This approach is certainly computationally intensive, in that it requires testing all pairs of needs across a range of values for each architecture variable. However, there are additional difficulties. First, the existence of step function utility curves could cause different behavior across different ranges of architecture variables. Should one therefore test over the whole architecture space, or over the whole utility curve range? I would advance that testing over the architecture space is more relevant, and that if conflicting or synergistic behavior is observed over some limited range, then that classification should be favored over 'orthogonal'.

Principle
Covariance of needs in a coupled architecture-stakeholder model will identify conflicting, synergistic and orthogonal needs.

One would also need to define rules for dominance of these classifications. It is conceivable that two needs could represent opposite behavior with respect to two different architecture variables. Should the stronger relationship be used? In part, the answer relates to how one intends to use the information. If conflicting / synergistic needs are to become rules of thumb for the architect, then only the strongest relationships would be highlighted, leaving out those with opposing behavior.

One way to narrow the permutations required for analysis would be to only compare inputs to a particular stakeholder. If comparing across stakeholders, one would have to find a way to control for causal relationships, where two flows are synergistic because the output of one is the input to the other. In this sense, processing for conflicting needs would be more the more interesting piece of information, as the current model essentially attempts to string together synergistic needs.

5.3.2. On Dynamics

There are 2 significant assumptions that this model makes with respect to the dynamics:

1. No time-phasing
2. The strength of one loop is independent of the strength of other paths or loops.

How Would Timing Work In A Benefit Model?

The time dimension is a particularly difficult one to model, in that it requires very detailed organizational models of stakeholders on the benefit side, and a detailed understanding of internal timelines for architectures. At first glance, one might also discount the importance of timing to NASA. It has often been joked that NASA has a discount rate of zero, in that a mission is worth the same to NASA whether it is launched this year or next year, provided it is successful.

While timing may not play a large role in benefit delivery for individual missions, it plays a significant role in the political and economic contexts NASA interacts with. Deadlines have long played a significant role in Congress' oversight with NASA, from Kennedy's "before this decade is out" to the current 2010 deadline for shuttle retirement. The choice of architecture impacts the fixed cost ratio for operations, which drives timing incentives for contractors, as well as the flexibility in responding to Executive deadline pressures or strategic initiatives.

Additionally, I have inferred that the architecture causes benefit at the same time it receives the resources it needs. In many cases, this is not realistic – the Congress provides investment well before it realizes the political benefits of that investment. This delay is bigger for loops where we see physical goods propagating, but smaller for certain types of information (like approval). Given the uncertainty in causality, I don't think it is necessarily feasible to model the timing of benefit being delivered to stakeholders, but we can still draw lessons based on a rough evaluation.

I divide stakeholders into *net creditors* (providing resources before the benefit is realized) and *net debtors* (receiving benefits before providing resources). Some types of creditors will hold power over the organization after their resources have been given over. While there exist fewer formalized protections for creditors in the intra-government case (as opposed to commercial finance), threat of future budget cuts and the re-appropriability of resources will define how much power stakeholders might have. Net debtors who hold important resources are a greater risk to the organization, in the sense that they have the opportunity to observe the architecture and the benefits before contributing resources.

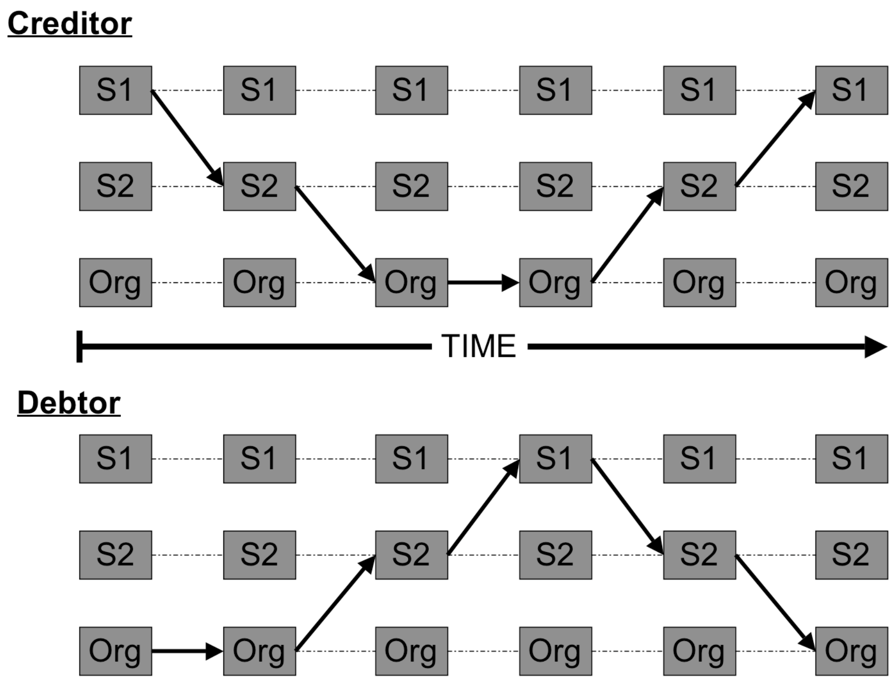


Figure 65 Time Expanded Benefit Transactions For Creditors and Debtors

Some simple case studies can help test these theories. For example, parliamentary oversight can occur relatively late in a design process, when design switching costs are high. In this sense, the Executive and Congress are debtors in the approval process (as opposed to the financial process). This would suggest that the concerns of the Executive should be tracked through the design process, which in the US consists primarily of the division of labour between NASA centers and contractors. However, these labour and project management decisions can be largely decoupled from the architectural decisions, so we would expect the Executive and Congress's feedback on the architecture proper to be more of a binary approval. As such, NASA's debtor relationship with Congress does not offer much power, because it can't appropriate resources (approval) based on the credit (design work) it extends.

The financial relationship between NASA and the Executive provides another case study, where the Executive is now a creditor to NASA. Architectures which enable variable costing decrease NASA's ability to lobby for additional funding, as the regret associated with not funding an additional mission is less than that for canceling an entire program with high fixed costs. However, the feedback loop between financing and direct benefits is much quicker than the approval process, which might caution against using power to realize desired outcomes, for fear the credit drying up in the future. If we think of the goal of stakeholder management as minimizing the use of power, we would view operational flexibility is a politically desirable quality.

The benefit that creditors provide need not be monetary. Science is also a net creditor of NASA, with respect to its role in goal selection. Scientists provide opinions on what science questions are most pressing, in return for which NASA makes a preliminary selection of landing sites. Individual scientists then invest time and choose research directions in order to position themselves relative to data and funding opportunities projected to arise out of the program, and at the end of the day, receive benefit if NASA builds hardware and makes consistent decisions to accomplish its stated science goals. This creditor relationship means that the architecture really doesn't have the opportunity to respond to scientist stakeholder feedback, unless the goals can be readily changed, or a unless a second generation program is planned. In this sense, multi-generational systems, like many Earth observation satellite programs, see much better stakeholder engagement and involvement in the architecture.

The other relevant dimension here is the duration over which benefit is delivered. Is benefit delivered incrementally through the project's implementation and operation, or is it delivered in a burst, only once the entire system is complete? For example, we can assume that political benefit deriving from spending in a given district will accrue over the life of the project, whereas science benefit only occurs when data is actually returned from the lunar surface. For incremental value delivery, we can imagine that there would be earlier stakeholder feedback. If there is a desire to include feedback in the design, then we have to ensure that the architecture has flexible goals. For a more concrete example, if a manned mission campaign is to be preceded by a robotic campaign, then we require that the manned mission architecture can switch science objective to respond to data gathered from robots. For point benefit delivery, we have no opportunities to test which aspects of the architecture affect benefit prior to system completion, which increases the need for interim reviews.

When Does Benefit Require Simultaneous Actions*?*

I think it is clear to the reader that many types of benefit require several things to fall in line at once. For example, new science data is not necessarily valuable without the funding to analyze it. The model as I have defined it searches only for paths through the network, assuming that a given input can be used to influence a given output.

For a first level analysis in only the benefit space, one could simply flag all stocks where multiple inputs are needed to modulate the output. One would then have to perform a search function back to the starting node to capture paths leading to the required additional flow(s). One criteria for selecting parallel paths might be commonality in the NASA output. Under this regime, one would have to represent trees with the root at the NASA input, and the leaves at the NASA outputs, as shown in the figure below.

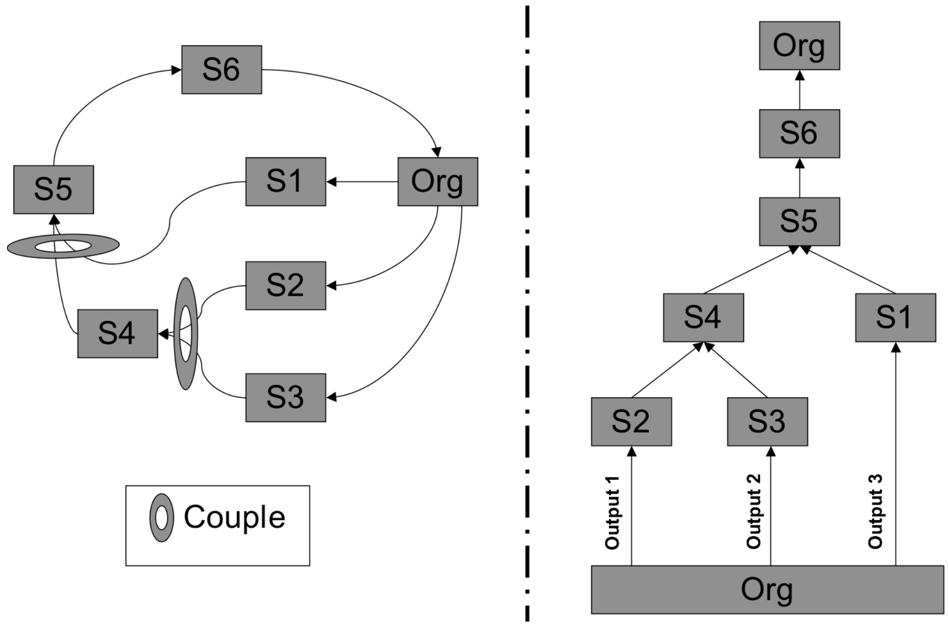


Figure 66 Value Loop Representation With Couples

More detailed analysis of this phenomena cannot rely on manual pairings of inputs. This likely requires definition of a 'physical' model, where the stock fill rate is actually defined by the flow rates on inputs.

5.3.3. On Outputs

There are two divergent contexts in which we can examine the outputs of this methodology. First, we can examine them in the context of modeling-assisted decision making process, and second, in the context of a traditional requirements engineering decision process.

Model-Assisted Decision Making

This section examines the possible concerns on the utility of stakeholder analysis in an environment where the architecture is being chosen with assistance from a large architecture model.

From a computational perspective, given a large architecture space which is computationally intractable as a whole, one would want to:

1. Run a stakeholder analysis to define what processes have to be included in the architecture space
2. Create a rough model of the architecture, match this to rough metrics for stakeholders, and throw out architectures that deliver little benefit

3. Create a more detailed model of the architecture, sorting for technical feasibility and technical metrics.
4. Use stakeholder analysis to define detailed metrics by which architecture should be evaluated, including soft ‘observable’ comparisons, then rate architectures across stakeholders, eliminating Pareto inefficient architectures.
5. Use detailed affordability, risk, policy robustness and value comparisons across architectures to select the winner.

Notice that model-assisted methods rely much more strongly on metrics. These methods also require different types of information. Specifically, they require that the architect input explicit tradeoffs when different metrics are used to evaluate benefit (as opposed when metrics are used to enforce constraints). Additionally, model-assisted methods force a distinction between hard (measurable) metrics and soft (observable) metrics. These soft metrics must be evaluated by the architect through comparisons within the architecture space. Goals play a smaller role in model-assisted methods, because there is no uncertainty as to the final design value.

Goals play a larger role where there is uncertainty in the final product – as such, encoding stakeholder needs as goals helps bracket the value of the final design. Goals and metrics are not opposing, in the sense that a model-assisted approach can be used first to define which goals are reasonable, and then further, to define the Metrics and Target Values by which the eventual design should be evaluated. This is very much in the spirit of the DoDAF metrics described above.

Requirements Engineering

For the sake of argument, I abstract the traditional requirements engineering process as follows :

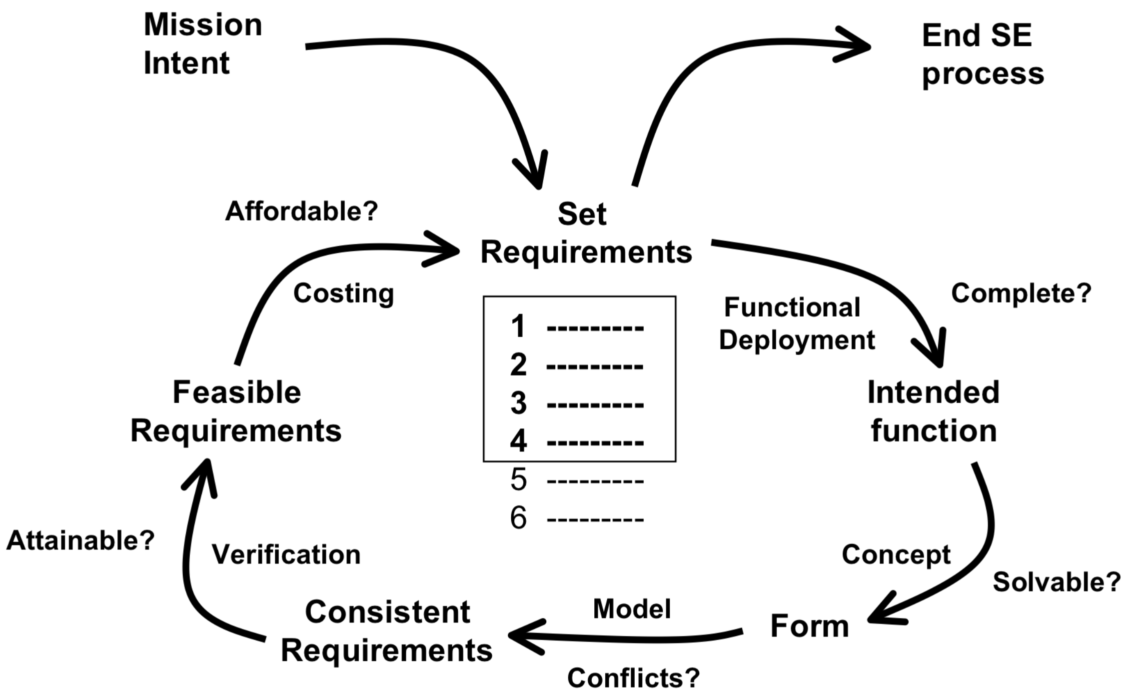


Figure 67 Traditional Requirements Engineering Process

(Adopted From Crawley ESD.34 Fall Lecture 3)

I have already shown how we can prioritize needs according to important stakeholders, and we can derive metrics that are representative of stakeholder value. However, we have not yet addressed how these conceptions might fare when pitted against typical organizational pressure on legacy, cost, schedule, performance shortfalls, within the requirements engineering process?

Many of these pressures are stakeholder-driven or overseen. Cost oversight is one the Congress' main roles – although some would argue the real responsibility is internal if the evaluating body doesn't have the technical expertise to understand cost trends. Use of legacy hardware is sometimes advanced by contractors looking to extend current contracts and the implementation of interfaces with legacy is primarily the contractor's responsibility. Past performance shortfalls linger in stakeholder consultations, influencing stakeholder strategies on setting their minimum requirements.

The essential tension that exists in this problem is a battle between building internal capabilities vs. delivering external benefit. For example, cutting requirements to meet a schedule deadline may help accomplish land people on the moon sooner, but conceivably with fewer science capabilities. We could re-express this tension as a competition between responding to stakeholders and achieving technical feasibility.

The easiest mental model to fit this problem is to consider stakeholder satisfaction as part of the performance space of the architecture. According to conventional system engineering wisdom, one can control a maximum of 2 of : Cost, Schedule and Performance.

One solution is therefore to assign internal owners to particular benefit delivery programs, particularly where value propositions are not easily encoded as technical requirements. If stakeholder satisfaction results from emergent behavior defined from a number of architectural values, then it is only logical that the concerns have to be managed across the breadth of the project, rather than locally. On the process side, this means that requirements trades have to be carefully scoped in order to capture the relevant benefit space and benefit-owners. I have already shown a method for determining the benefit sensitivity of a particular architecture variable – obviously if a requirements trade has no benefit implications it should not considered in the trade.

I postulate that one of most common failure points of benefit analysis is overscoping the architecture. Imagine if stakeholders are allowed to express possible objectives with widely different architecture scopes. Over time, the architecting process narrows the architecture space, in response to cost constraints, schedule deadlines, etc. The natural response is to eliminate those objectives that don't fit into the new space, despite the fact that the stakeholder's needs remain. Moreover, throwing out those objectives suggests that all stakeholder needs are malleable and possibly infirm. This problem does not arise because stakeholders are inherently unreasonable, but rather because the questions asked of them are typically open-ended. Working with stakeholder to narrow these objectives as the architecture space narrows is essential if the architect is going to attempt to track benefit as a performance metric.

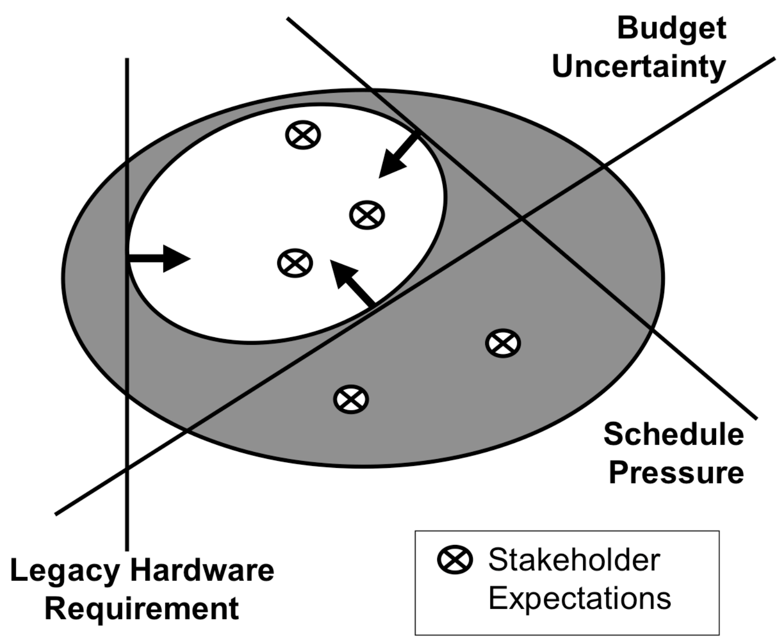


Figure 68 Shrinking Architecture Space

The key contribution from this thesis to requirements engineering is that value mapping allows the architect to scope out all of the stakeholder considerations relevant to the problem, so that when it comes to validating the design, one understand the dimensions along which the design needs to be evaluated. Given that not all stakeholder needs can be encoded as requirements, but that they are observable from an architecture, this means that we need checks built into design reviews that examine these soft consideration across a comparison set of architectures.

In a model-assisted decision frame, this is easily done. However, as can be seen from the NASA design review model, where benefit considerations are almost non-existent, this is more difficult. I don't believe that it makes sense to ask the reviewers (and stakeholders) to determine whether a given architecture meets these needs, because the tendency will be to "check the box". Therefore, I believe that where alternative architectures are brought forth or considered at a design review, particularly for trades, the benefit should be captured as a dimension of evaluation.

I postulate that stakeholders whose stake in the organization depends more on implementation than operation will be more likely to care about singular architectural variables. If given the opportunity for broad input on the architecture, these actors will use couplings in the design to argue indirectly for the architecture that favors them. For example, a company focused on robotics and in-space assembly will favor an architecture that involves EOR and LOR over a direct mission. The point is that stakeholders whose benefit derives from single architectural variables will nevertheless attempt to extend their influence to include more architectural variables, in particular because it can be more difficult to discern vested interest. Therefore, it could prove desirable, though not necessarily feasible, to limit consultations with stakeholders to those aspects directly related to their benefit, leaving decisions about design couplings to the architect.

With respect to stakeholders who derive benefit from the operation of the system, there may be cases where stakeholders are only concerned with a subset of the architecture. For example, those scientist concerned with lunar soil may only be concerned with surface operations, given that they have access to (assumed) homogeneous samples wherever the activities are located on the surface.

What use is this information? I have made reference several times to segregating stakeholder involvement as a function of their interests. At the consultation stage, this shouldn't be a significant concern, in the sense that consultations are typically structured to capture as much input as possible. However, at the evaluation stage, we should only evaluate stakeholder benefit for the aspects of the architecture that directly concern that stakeholder, rather than attempting to evaluate a stakeholder's opinions on all aspects of the architecture.

This is necessarily a soft consideration, given the variation in benefit and design processes. More important than capturing benefit in the design process, it is important to align people in the organization to benefit, as highlighted above.

What are the possible organizational alignment principles vis-à-vis managing for stakeholder value?

I've already touched on some of the organizational principles informed by this work, but I have collected them and expanded on the below.

1. The organization should be aligned with the value outputs it produces, particularly at the architecture decision level. Valued outputs should be clearly traceable to responsibilities, processes, and incentives within the organization. This means have individuals to represent and analyze the needs of stakeholders who benefit from the architecture, in proportion to the organization's stakeholder priorities.

2. Identifying value loops helps an organization understand who contributes to the provision of the inputs the organization requires.

3. Organizational representatives for benefit streams should be proportionately represented at design reviews, but only for those stakeholders which are architecture discriminators. Stakeholder who receive benefit that is invariant within the architecture space should not be consulted at the architecture definition stage.

4. Where architectural choices settle conflicts between stakeholders, these decision should be expressed to the relevant stakeholders, to build buy-in and communicate how their needs are being met.

5. Given the length of value loops, and the supposition that a given player only has visibility to 2 flows in front and behind, then it may be difficult to identify the root provider of value. There are opportunities with stakeholders to improve the branding and the gain of these loops for those stakeholders who don't have visibility back to NASA. Furthermore, reducing the number stakeholders and value flows between the organization and the end beneficiary will almost universally improve traceability.

6. Building common understanding *among* stakeholders can help reinforce key messages in a distributed fashion. For example, reinforcing a message that NASA provides health benefits to the population, and strengthening communications opportunities among relevant stakeholders, may eventually lead to a conventional wisdom that "NASA does life science research", at which stage stakeholders will form a distributed communications network for NASA. Likewise, the value of reinforcing aspects of NASA's work that are already in the conventional wisdom may not prove to be high-leverage activities.

6. Future Work and Conclusions

In this thesis, I have explored the feasibility of making architectural decisions based on stakeholder analysis and externally-delivered value. I have shown that using stakeholder networks can help represent the complexity of indirect benefit delivery. I have also advanced a numerical methodology for encoding stakeholder preferences, which can be used to determine the relative prioritization of the outputs of the organization. Furthermore, I have created and tested a framework for linking benefit models to architecture models, in order to confirm that benefit models can indeed be used to differentiate between architectures.

For reference I have collated the principles derived in this thesis below:

1. Internal assets restrict the input-output connectivity of a stakeholder model

2. Network diagrams can help represent and book keep complex value flows characterized by indirect value delivery

3. Indirect benefit delivery forces consideration of value loops over simpler transaction models.

4. Computation on value flows can discover discrepancies between how different groups perceive the mission of the organization

5. Weighted outputs provide an indication of how the organization should align its products to create strong feedback loops to inputs of importance

6. Stakeholder inputs should be traceable to metrics and criteria at the architecture evaluation phase

7. Not all benefit flows will differentiate between architectures – some types of benefit will be produced regardless of which architecture is chosen

8. The outputs of the organization in a value network model define the space of proximate metrics required for architecture evaluation.

9. The human ability to conceptualize the level of detail in the model is an important component of success when attributes of the benefit are observable but not decomposable.

10. Covariance of needs in a coupled architecture-stakeholder model will identify conflicting, synergistic and orthogonal needs

There are a numbers directions of future work on this topic, given that it quantitative methods for 'soft' engineering and management considerations are becoming tractable with new analytical techniques.

Stakeholder Models

From a theoretical standpoint, there are three big question to address on stakeholder models:

1. When does benefit require simultaneous inputs? How can these constraints be effectively represented within the current framework?

2. How does the network representation of stakeholders enable the architect to identify opportunities for new benefit flows or connectivity between stakeholders? This could be framed either in terms of maximizing inputs or in terms of providing alternative paths to enable policy flexibility.

3. How do value loops function when stakeholders form coalitions? This would require understanding the terms on which stakeholders create coalitions, and the action they would take.

In terms of the baseline modeling structure created, there are also several areas that would be interesting to investigate. Namely, it would be interesting to build a second level of depth into a stakeholder network model, to investigate whether the decomposition of needs provides more or less accountability for decisions. Additionally, it would be worthwhile investigating the calibration of a limited subset of loops, but with the understanding that traceability of impact makes this an enormous challenge. This work would be particularly useful in studying conversions of flow types, and its impact on traceability to the root provider of value.

It would also be interesting to interface the current network model to an internal model of NASA, to better understand how inputs translate into outputs on a more operational level than the current long term architecting approach taken in this thesis.

Finally, it would be interesting to expand on the competition aspect of stakeholder power. One could relatively quickly expand the current competition framework to include multiple layers of competition within a value chain. A more in-depth study of competition would have to define the benefit of competition explicitly in terms of margins (or the non-monetary equivalents of margins), in order to correlate levels of competition with transaction costs or availability of resources.

Proximate Metrics and Architectures

First and foremost, the development of a complete set of proximate metrics with respect to an actual architecture space is needed. While science metrics for other applications have been well developed in the literature, there is a definite hole in the literature on exploration and planetary surface science metrics.

The next step would be to create a coupled model of stakeholders and architectures, which would necessarily include constraints. In particular, cost constraints would be the most interesting to include, to enable a value equals benefit at cost argument. This exercise would have to wrestle with a number of concerns highlighted in Section 5.3.3, namely whether functions or forms must be specified to compute benefit, and what to do if the benefit to different stakeholders occurs at different phases of the life of the architecture.

I think there is also significant work to be done on the representation of benefit for different architecture. Some sketches were provided in this thesis, but the problem of illustrating an architecture space with physical, cost, and stakeholder constraints, and different functions for benefit and cost within the feasible space remains. I continue to believe that the use of visual media will be essential if this methodology is to be effective.

Organizational Studies

As the reader has most certainly noticed, much of this thesis is concerned with phenomena created by large engineering organizations. The incentives and structure within organizations like NASA have rise to the incomplete benefit space exploration that motivated this thesis. Any successful methodology with the same scope of this thesis has to make very clear how it will integrate within current organizations.

There is still significant work to be done on the motivation for this research: Expressing and demonstrating with historical examples *why* it is so difficult to capture non-technical requirements. While some organizational studies certainly exist with respect to engineering failures, the literature would really benefit for a clear set of case studies on the structures that lead to an incomplete consideration of the benefit space, particularly in the aerospace industry.

I think future work in this area would also have to include how decision-support tools interface in actuality with organizational processes, particularly for decisions on stakeholder benefit, which have historically been made on very rough heuristics.

7. Appendix 1 : Individual Value Flows

The table below provides a description for each type of link in the model, listed alphabetically.

Benefit Flow	Description
Access to highly visible events	Capabilities that enable greater depth of (non-NASA) media coverage. Video cameras on spacecraft, live interview time with astronauts, etc.
Commercial launch	Commercial launch services purchased by economic players, NASA, and security. Ex. Delta 4 flight to orbit a satellite.
Corporate taxes	Taxes paid by firms in the economy.
Economy opinions and policy support	The view of NASA as a whole and with respect to specific programs that is espoused by contractors to the US Congress as well as the media. Ex. lobbying the congress by Boeing, or contractor interviews on their bids for the CEV in Popular Mechanics.
Educator opinions and policy support	The feedback from K-12 teachers and university professors to the media and to the US Congress on the provision of educational material by NASA. This does not cover research opinions, which are lumped under Science.
Exploration systems	The hardware and software systems provided in return for NASA contracts. Ex. Shuttle SRBs.
Funding	The annual budget and budget outlooks provided by the Congress to NASA, which represents the only source of income for NASA in this model.
Goods and services, inc. health, derived from space technology	This represents the technology transfer of space technology and space-derived science knowledge to products for the American people. Ex. molecular biology experiments onboard ISS that aid in the development of a commercial drug, or more directly from NASA technology, velcro.
Human Exploration First Events	Humans in new places, not necessarily on a planetary surface. Landing in new locations on the same planet would count as a new event. Ex. Landing at the lunar pole.
Humans in Space Events	Projected events that show humans in space but not exploring a planetary body. This would include test flights leading up to a new exploration event. Ex. A crew exchange on the ISS.
Informative and entertaining media content	Covers all media coverage of NASA, from spacecraft launches to new images returned from planetary missions. Separated into entertaining and informative, which are not mutually exclusive, in recognition that event-centric coverage (launch) has a different audience from science-results coverage.

International Agreements	Agreements or treaties signed between nations for cooperation in space. Would include collaborative projects (ISS), exchanges (modules for astronaut flights) or NASA supplied hardware for international flights. Agreements are nec. but not suf. for actual hardware exchange. Actual hardware exchange are modelled separately.
International launch services	Launch of NASA cargo or people, typically government controlled launch faclities (Soyuz), but also including commercial launch services purchased internationally (Ariane, DNEPR) which require some political mediation.
Internationally provided space systems	Modules, instruments, or capabilities provided under international agreement. Does not distinguish between systems provided for an international project and systems provided for a NASA mission.
Mission and Event Content	The web, video and audio content that NASA makes available for direct consumption by stakeholders . Examples include the Mars pathfinder website and NASA TV broadcasts from the ISS. This does not include technical data, or the frequency or interest of the events, just the extent to which NASA publishes content.
NASA Contract funding	Contracts to industry for exploration hardware, and the associated analysis. Ex. Canadarm2 acquisition
NASA educational content	Content (video, written, or exhibits or speeches) specifically designed to be used by teachers (K12 or at the university level), created by NASA.
NASA Instruments and Modules	NASA instruments provided to international partners on national missions. This is the converse of 'internationally provided space systems'.
NASA Launch and Space Services	Use of NASA infrastructure (Deep Space Network, TDRSS) or launch services (Shuttle) by security or international partners.
NASA Market funding	Funding for systems or services that are partially or wholly motivated by a desire to create a new market, typically to achieve cost reduction or improve performance. For example, ISS resupply contracts.
NASA Science Events	Presentation of science knowledge on a NASA mission, or the launch of a primarily-science mission. Ex. Release of new Hubble photos.
NASA Science Funding	Contracts for analysis of science data or acquisition of hardware from scientist in universities or research institutions. This includes exploration and technology relevant analysis (ex. engine flow solvers), not just 'pure' science.
NASA Space Technology	Two main categories - technology relevant to future space applications, and technology relevant to earth applications (spin-offs). Ex. automated rendezvous and docking and velcro, respectively.

NASA Space Technology Demonstration Events	Events that are primarily tech demonstrations, may be manned or unmanned. Ex. Spacecraft testing an autonomous rendezvous and docking procedure.
Participation in international exploration missions	The benefits derived in exchange for supplying instruments and modules to an international mission, including foreign political capital, mission and event content, and sharing of cost.
Participation in NASA-led exploration mission	Benefits of participating in NASA-led exploration missions, including transportation to destination, spacecraft bus, as well as PR content at home. Received in exchange for internationally provided space systems.
Personal Taxes	Taxes paid to the government on income. Given that there is no federal goods and services tax, this is most strongly influenced by employment.
Plans and Progress Reports	The architecture's ability to provide regular reports, to show progress in a sequential, measured fashion. This flow is only provided to the stakeholders who might have a role in the planning. Whether or not the architect is providing plans the stakeholder agrees or disagrees with is captured by the projected value flows, not here.
Policy direction	This captures a number of elements. 1) Congressional feedback on plans and progress reports, including directives that carry possible funding implications in the future 2) Throughput of international agreements from international partners to NASA 3) Executive direction on the types of missions, as well as characteristics of those missions (ex. near term demonstrations of progress)
Political support (votes)	This is a special subset of Public Opinion, that deals with the election of Congress and the Executive. It is intended to capture the extent to which a given administration is associated with NASA's actions, postive and negative.
Protection against claims of sovereignty on planetary bodies	Primarily presence in space and on planets, but also imaging that could be used to document abuses of the Outer Space Treaty. As this is not a strong justification currently, it is binary - presence or no presence on a planet. This is provided to the Congress, rather than the people, because it is not a tangible benefit, and because the Congress is specifically chartered with the stewardship of safety.
Public opinions and policy support	Specific feedback provided to Congress, as well as 'concensus' opinions given in the media, on all aspects of NASA performance, but primarily those relevant to the US people, such as inspiration, space-derived goods and services, etc. For example, popular support for the Mars exploration rovers, as evidenced by increased media coverage, including interviews of students and people on the street.

Science and engineering inspired students	Students are provided by the US People to the Educators, to the extent that they have been inspired by NASA to pursue technical careers.
Science data	Observations and measurements captured by NASA, both in space and on planetary surfaces. Ex. radar altimetry of the moon, radiation levels in LEO.
Science knowledge	The knowledge gained from NASA exploration activities, as processed and created by scientists from science data. Ex. gravity model of the moon, presence of water at the lunar pole.
Science opinions and policy support	This captures both science opinions on NASA provided to the media (ex. 'NASA is cutting lifescience funding!') and science feedback to NASA directly on what areas merit attention - such as the relative worth of going to the lunar pole vs in an equatorial site.
Security benefits	The protection from harm and invasion, a feeling of security. This is recognized in the model as another mechanism by which activities in space contribute to quality of life.
Security Funding	The money allocated to defense activities. This quantitiy is present to show that there are competing agents for the government's budget, and to provide the source for security's contract funding in the model.
Security opinions and policy support	The support or lack thereof of NASA expressed by various security organizations, particularly with respect to joint programs (Space Shuttle) and shared industrial base. Ex. US air force largely pulling out of Space Shuttle as a launch vehicle, and creation of another EELV program, after the loss of Challenger.
Skilled workforce	The result of training students in a specific discipline. Educators are the source of skilled workforce. The assumption made is that each stakeholder has a stock of human capital, which increases the skills of their workforce, but these workers are not transfered between stakeholders, in order to simplify the model. Ex. MIT training aerospace engineers, who go to work at Lockheed.
Space Acquired Data	Measurements relevant to security and commercial interests in space - knowledge that is not particularly scientifically interesting, but which is valuable for building and operating space technology. Ex. fine measurements of the micrometeroid frequency in GEO.
Space resource knowledge	Knowledge relevant to commercial interests for mining, such as the prevalence of hydrogen at the lunar poles. This captures a very specific form of science data
Space tourism services	The market created within the economy for space tourism opportunities, which may or may not be derived directly from NASA, but nevertheless represent one of the most tangible offshoots of the space program to the US People. Ex. suborbital flights

	on SpaceShipOne, or soyuz flights to the ISS.
Stable and rewarding employment	The extent to which an architecture provides employment to NASA employees, and the relative certainty that the project will not be terminated or create layoffs. For example, a selection of NASA as prime contractor woud increase employment by NASA, and decrease that of contractors. Competiting forms of stable employment are listed in the model, originating from other stakeholders.
Unmanned Exploration First Events	New exploration events that represent a significant first. This is differentiated from Science events if the 'First' is more compelling or interesting than the 'Science'. The presentation of the science data gathered from an exploration event might merit a secondary NASA Science Event. Ex. NASA's Deep Impact : Flying a spacecraft through a comet tail

The table below indicates the values that I chose for the model. Kano Must Haves are shown as '5', One Dimensionals as '3' and Exciters as '1', to match the implementation in OPN. Likewise, for the importance scale, '5' is high and '1' is low.

To NASA	**From**	**Kano**	**Importance**	**Value**
Funding	Exec & Cong	5	5	1.00
Policy Direction	Exec & Cong	5	4	0.78
Media Entertainment and Information	Media	3	4	0.26
Skilled and motivated workforce	Educators	5	4	0.78
Commercial launch services	Economy	5	5	1.00
Exploration systems	Economy	5	5	1.00
Science knowledge	Science	1	3	0.06
Science systems	Science	5	3	0.55
Science opinions and policy support	Science	5	2	0.33
International launch services	Int Part	5	3	0.55
Internationally provided space systems	Int Part	1	3	0.06
Participation in international exploration mission	Int Part	1	2	0.04
To Executive and Congress	**From**	**Kano**	**Importance**	**Value**
Protection against claims of sovereignty in space	NASA	5	1	0.10

Plans and Progress Reports	NASA	5	3	0.55
NASA Mission and Event Content	NASA	1	2	0.04
Media Entertainment and Information	Media	3	4	0.26
Educator opinions and policy support	Educators	1	1	0.01
Economy opinions and policy support	Economy	1	2	0.04
Corporate Taxes	Economy	5	1	0.10
Science opinions and policy support	Science	1	1	0.01
International agreements	Int Part	3	4	0.26
Security opinions and Policy Support	Security	3	3	0.19
Protection against claims of sovereignty in space	Security	5	2	0.33
Political Support (Votes)	US People	5	5	1.00
Taxes (should this be marginal taxes?)	US People	3	2	0.11
Public opinion and policy support	US People	3	4	0.26
To Media	**From**	**Kano**	**Importance**	**Value**
Plans and Progress Reports	NASA	1	2	0.04
Access to highly visible events	NASA	1	3	0.06
NASA Mission and Event Content	NASA	1	2	0.04
Humans in Space Events	NASA	5	3	0.55
Human Exploration First Events	NASA	5	5	1.00
Unmanned Exploration First Events	NASA	5	4	0.78
NASA Science Events	NASA	3	4	0.26
NASA Space technology demontration Events	NASA	3	3	0.18
Educator opinions and policy support	Educators	1	3	0.06
Economy opinions and policy support	Economy	1	1	0.01
Science knowledge	Science	1	2	0.04
Science opinions and policy support	Science	1	2	0.04
Public opinion and policy support	US People	1	2	0.04
To Educators	**From**	**Kano**	**Importance**	**Value**

NASA Mission and Event Content	NASA	1	2	0.04
NASA education material	NASA	1	3	0.06
Media Entertainment and Information	Media	1	3	0.06
Science knowledge	Science	3	4	0.26
Science and Eng Inspired Students	US People	5	5	1.00
To Economy	**From**	**Kano**	**Importance**	**Value**
NASA Market funding	NASA	3	3	0.19
NASA contract funding	NASA	3	4	0.26
Space resource knowledge	NASA	3	3	0.19
NASA launch and space services	NASA	1	2	0.04
NASA space technology	NASA	3	3	0.19
Space acquired data	NASA	3	3	0.19
Plans and progress reports	NASA	3	5	0.34
Media Entertainment and Information	Media	3	3	0.19
Skilled and motivated workforce	Educators	5	5	1.00
Science knowledge	Science	1	2	0.04
Security Contract Funding	Security	5	5	1.00
To Science	**From**	**Kano**	**Importance**	**Value**
NASA science funding	NASA	5	5	1.00
NASA space technology	NASA	3	3	0.19
Science data	NASA	5	5	1.00
Space acquired data	NASA	3	4	0.26
Plans and progress reports	NASA	3	4	0.26
Media Entertainment and Information	Media	1	3	0.06
Skilled and motivated workforce	Educators	5	5	1.00
To International Partners	**From**	**Kano**	**Importance**	**Value**
NASA launch and space services	NASA	1	4	0.09
Plans and progress reports	NASA	5	4	0.78
NASA instruments and modules	NASA	1	2	0.04
Participation in NASA Exploration Missions	NASA	3	5	0.33
International agreements	Exec & Cong	3	4	0.26
Media Entertainment and Information	Media	1	3	0.06
To Security	**From**	**Kano**	**Importance**	**Value**
NASA space technology	NASA	1	2	0.04

NASA launch and space services	NASA	1	3	0.06
Space acquired data	NASA	3	4	0.26
Media Entertainment and Information	Media	1	3	0.06
Skilled and motivated workforce	Educators	5	5	1.00
Commercial launch services	Economy	5	5	1.00
Science knowledge	Science	1	3	0.06
To US People	**From**	**Kano**	**Importance**	**Value**
Stable and rewarding employment	NASA	5	4	0.78
NASA Mission and Event Content	NASA	1	3	0.06
Media Entertainment and Information	Media	3	4	0.26
Stable and rewarding employment	Educators	5	2	0.33
Stable and rewarding employment	Economy	5	5	1.00
Space tourism services	Economy	1	3	0.06
Goods and services, including health technology, derived from space technology	Economy	1	2	0.04
Stable and rewarding employment	Science	5	3	0.55
Stable and rewarding employment	Security	5	4	0.78
Security benefits	Security	5	5	1.00

8. Appendix 2 : Building a Benefit Network Model in OPN

Key Attributes of OPN Model

1) Each flow modifies value, using the statement: v = v*k1*i1*c1 where the numbers are indices for the Kano, Importance, and Competition. All of these values have to be initialized.

2) The path through the system is traced based on flows. One variable, 'path' , is a concatenated string containing the names of all the flows. The statement is:

   path=path+ "Security Opinions"

   It is important that all similar flows have the exact same spelling, because some of the post-processing in Excel is case-sensitive.

3) The model checks to make sure each stakeholder is only visited once. There is a variable for visits, initialized to zero. This variable is then incremented by any process that is going towards the node (ex. people = people+1). All links that connect to a node therefore have to have a logical check, people = =1 , to ensure that node has not yet been visited. Alternatively, if you wanted to allow loops, you could set this relative to a variable, ex people <= max, max=2.

4) I have a counter to determine the length of a loop. Every process increments length = length +1

5) In order to get the model to run in a finite length of time, I put a cap on the value of v. This is encoded on the links that exit a node and go to the outgoing process, and is written v<a, where a in my model works as low as 0.001. There is an additional logical constraints, see #1 below (stop stakeholders).

6) Each stakeholder in my model is composed of a series of objects, the internal assets. Together, these internal assets form the stakeholder node. The internal assets provide connectivity between inputs and outputs, to prevent any input from being paired with any output (which might result in an illogical pairing).

7) All inputs to NASA are collected at a centralized 'Report Node'.

Getting the Model Stop at Stakeholders

1) I have an outgoing process linked to each node. The link is conditional on a flag, ex. STOPPeople. The idea is open this path up to tokens, and prevents tokens from taking any other outgoing path . Therefore, all the other outgoing links from the node need a STOPPeople==0 condition (in addition to the v>a condition).

2) The results have to be collected from a separate ReportStakeholder node.

Getting the Model Stop at Stakeholders

1) I have a process that leaves from the initializing node. It has a conditional link, only for STARTPeople == 1. This process only has code to set the starting node's visited flag to one (people = people + 1). This process has to be linked to all internal assets in the node, which will necessarily create duplicates. Duplicates can be handled in the post-processing.

Post Processing

1) Process for duplicates (have an algorithm).
2) Rank by v value
3) Determine stakeholder incidence in high-value loops
4) Determine NASA output incidence in high value loops
5) Determine NASA inputs incidence in high value loops
6) Collect START and STOP data pairs for each stakeholder at a variety of levels.

Couple of Flaws I've Found in OPN:

1) It is very difficult to query the token's location in the model. As such, any path-related algorithms have to be decentralized, in the sense that the code has to be embedded at its origin, not at its destination.
2) I couldn't figure out how to assign variables to a matrix (without using a string) of uncertain size – therefore, all nodes (stakeholders) are referenced using separated variables.
3) You can't modify a variable in a process, then reference it.

   For example:
   klo = 0.5
   khi = 1.0
   k=klo
   k=khi
   a=k

   Comes out a = 0.5 instead of a=1.0

3) If viewing report tokens, need to click on another object in list, then back to the report, in order to fully refresh list of tokens.

9. Appendix 3 : Code for Metrics

9.1. Science Data and Space Resource Knowledge Metrics

Total Crew Science Hours
#Fixed and Made Up Variables
numMissions=10
MaxCrewObservationDays=6*30
UnmannedObservationDays=360
numScienceInstruments=10
UnmannedDiscount=1/4
EVAhours = 6
ScienceTimeFraction = 0.4

#Calculations

CrewObserveDays=crew*duration
CrewScienceHours = CrewObserveDays*EVAhours*ScienceTimeFraction
TotalCrewScienceHours = CrewScienceHours*numMissions

#Amount of Data Collected Value Table
DataAmountZeroPC = 0
DataAmountTenPC = 0.5*numScienceInstruments
DataAmountNinetyPC = 10*numScienceInstruments
DataAmountOneHPC = 40*numScienceInstruments

Amount of Data Collected Calculation
DataAmount = TotalCrewScienceHours
DataAmountValue = Interpolator(DataAmount, DataAmountZeroPC,
DataAmountTenPC, DataAmountNinetyPC, DataAmountOneHPC)

Mass Per Instrument
MassPerInstrument = sciencemass/numScienceInstruments

MPIZeroPC = 0
MPITenPC = 1
MPINinetyPC = 100
MPIOneHPC = 1000

MPIValue = Interpolator(MassPerInstrument,
MPIZeroPC,MPITenPC,MPINinetyPC,MPIOneHPC)

Roving Area
RovingArea = 3.14*roverrange*roverrange

Roving Area Value Table

RovingAreaZeroPC = 0
RovingAreaTenPC = 3.14*0.1*0.1
RovingAreaNinetyPC = 3.14*30*30
RovingAreaOneHPC = 3.14*100*100

Roving Area Value
RovingAreaValue =
Interpolator(RovingArea,RovingAreaZeroPC,RovingAreaTenPC,RovingAreaNinetyPC,
RovingAreaOneHPC)

Data Quality
#Because rover speed is not traded, set its value to 1
RoverSpeed = 30
RoverSpeedValue = 1

DataQuality = MPIValue*access*RovingAreaValue*RoverSpeedValue

Science Data
ScienceData = DataAmountValue*DataQualityValue

Space Resource Knowledge
SpaceResourceKnowledge = Science Data

9.2. NASA Space and Launch Services Metric

Heavy Lift Value
HeavyLiftZeroPC = 23
HeavyLiftTenPC = 25
HeavyLiftNinetyPC = 60
HeavyLiftOneHPC = 130

HeavyLiftValue = Interpolator(HeavyLift,HeavyLiftZeroPC,HeavyLiftTenPC,
HeavyLiftNinetyPC, HeavyLiftOneHPC)

NASA Launch Services
NASALaunchServices = HeavyLiftValue

9.3. Science Funding Metric

Here we mean money for science instruments that go to the moon
not science funding that helps design exploration hardware

FundingPerKilo = 100000

SciFund = FundingPerKilo*ScienceMass

# Science Funding Table
SciFundZeroPC = 0
SciFundTenPC = 10000000
ScieFundNinetyPC = 100000000
SciFundOneHPC = 1000000000

Science Funding Value
SciFundValue = Interpolator(SciFund,SciFundZeroPC,SciFundTenPC, ScieFundNinetyPC, SciFundOneHPC)

9.4. Humans In Space Events Metric

# Crew Inspiration Value Table
CrewInspireZeroPC = 0
CrewInspireTenPC = 0.5
CrewInspireNinetyPC = 3
CrewInspireOneHPC = 10

Crew Inspiration Value
CrewInspireValue = Interpolator(Crew,CrewInspireZeroPC, CrewInspireTenPC, CrewInspireNinetyPC, CrewInspireOneHPC)

# Duration Inspiration Table
DuraZeroPC = 0
DuraTenPC = 1
DuraNinetyPC = 7
DuraOneHPC = 90

Duration Value
DuraInspValue = Interpolator(duration,DuraZeroPC,DuraTenPC,DuraNinetyPC,DuraOneHPC)

FlightsPerYear = 2

Flights Per Year Table

FlightsZeroPC = 0
FlightsTenPC = 0
FlightsNinetyPC = 3
FlightsOneHPC = 6

Flight Value

FlightsValue = Interpolator(FlightsPerYear, FlightsZeroPC, FlightsTenPC,FlightsNinetyPC,FlightsOneHPC)

Assumed Values

#Assume EVAs are proportional to duration
EVAValue = DuraInspValue
VehicleTransferEventsValue = 1
TotalTimeinSpaceValue = 1

Humans in Space Value
HumansInSpaceEventsValue = CrewInspireValue*DuraInspValue*EVAValue*VehicleTransferEventsValue*TotalTimeinSpaceValue*FlightsValue

9.5. Human Exploration Firsts Events Metric

Global Access Human Exploration Firsts Locations
SouthPole = 1
NorthPole = 1
LunarFarside = 1
SouthHighLat = 1
NorthHighLat = 1
ModernEquatorial = 1

Equatorial Access Human Exploration Firsts Locations
ModernEquatorial = 1

LunarNightStay = 1

Assumptions
No habitats, basing, power production, or resource collection in this phase.

RevisitsPerSite = 0

Rate of New Events
PotentialRateofNewVisits = FlightsPerYear/(RevisitsPerSite+1)

#This could use some work
#New Visit Rate Table
NewVisitZeroPC=0
NewVisitTenPC=0.3
NewVisitNinetyPC=2
NewVisitOneHPC=3

NewVisitRateValue =
Interpolator(PotentialRateofNewVisits,NewVisitsZeroPC,NewVisitsTenPC,NewVisitsNinetyPC,NewVisitsOneHPC)

Total New Events
TotalExpEvents =
SouthPole+NorthPole+LunarFarside+LunarNightStay+NorthHighLat+SouthHighLat+ModernEquatorial

TotalExpEventsZeroPC = 0
TotalExpEventsTenPC = 0.5
TotalExpEventsNinetyPC = 3
TotalExpEventsOneHPC = 25

TotalExpValue =
Interpolator(TotalExpEvents,TotalExpEventsZeroPC,TotalExpEventsTenPC,TotalExpEventsNinetyPC,TotalExpEventsOneHPC)

Human Exploration Firsts
ExpFirsts = TotalExpValue*NewVisitRateValue

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