A Systematic Concept Exploration Methodology Applied to Venus In Situ Explorer

Jarret M. Lafleur, Gregory Lantoine*, Andrew L. Hensley*, Ghislain J. Retaureau*, Kara M. Kranzusch*, Joseph W. Hickman*, Marc N. Wilson*, and Daniel P. Schrage†*

Georgia Institute of Technology
Atlanta, Georgia 30332

ABSTRACT

One of the most critical tasks in the design of a complex system is the initial conversion of mission or program objectives into a baseline system architecture. Presented in this paper is a methodology to aid in this process that is frequently used for aerospace problems at the Georgia Institute of Technology. In this paper, the methodology is applied to initial concept formulation for the Venus In Situ Explorer (VISE) mission. Five primary steps are outlined which encompass program objective definition through evaluation of candidate designs. Tools covered include the Analytic Hierarchy Process (AHP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), and morphological matrices. Direction is given for the application of modeling and simulation as well as for subsequent iterations of the process. The paper covers both theoretical and practical aspects of the tools and process in the context of the VISE example, and it is hoped that this methodology may find future use in interplanetary probe design.

1. INTRODUCTION

One of the most critical tasks in the design of a complex engineering system is the initial conversion of mission or program objectives and requirements into a baseline system architecture. In completing this task, the challenge exists to comprehensively but efficiently explore the global trade space of potential designs. The comprehensiveness of such a search is particularly important for advanced exploration systems for which little or no historical precedent exists and for which reliance on engineering mindsets from previous projects may produce a bias toward suboptimal solutions. However, such a search must also be accomplished in a time-efficient manner since thorough analysis of all possible designs could easily span years.

Systems analysis problems of this type have become a staple of the graduate aerospace engineering curriculum at the Georgia Institute of Technology, and one methodology which has seen wide use in framing such problems is shown in Figure 1. This generic integrated product/process development (IPPD) methodology ties elements of systems and quality engineering into a top-down design decision support process, and it includes elements of both quantitative and qualitative systems analysis. This methodology has been taught and implemented for numerous fixed-wing aircraft, rotorcraft, and spacecraft design projects at Georgia Tech over nearly 15 years. This paper provides an illustration of how the Georgia Tech generic IPPD methodology and its associated tools may be systematically applied

* Graduate Student, Daniel Guggenheim School of Aerospace Engineering
† Professor, Daniel Guggenheim School of Aerospace Engineering

to the initial stages of design for an interplanetary robotic mission. Key steps are illustrated for the example of the Venus In Situ Explorer (VISE) mission proposed as part of the 2006 NASA Solar System Exploration Roadmap[2].

VISE is one of six New-Frontiers-class missions that NASA addresses in the 30-year scope of its 2006 Solar System Exploration Roadmap. It is also specifically mentioned by NASA as a candidate mission for NF-3 mission proposals due in early 2009.[3] With a launch perhaps as early as 2013, VISE is envisioned as an aerial mission to study Venus' atmospheric composition as well as descend briefly to the surface to acquire samples for later analysis at more benign altitudes (see Figure 2).[2,4] With these surface visits, VISE represents an opportunity to contribute significantly to a limited body of knowledge regarding Venus' surface; as indicated by Figure 3, global missions per year to Venus declined severely in the late 1980s, and no vehicle has been to the surface in over 20 years. Additionally, in over 20 years no vehicle has made in situ measurements of Venus' atmosphere. Common to both VISE and its envisioned Flagship-class successor, Venus Mobile Explorer, is the challenge to operate under the extreme temperatures (730 K) and pressures (90 atm) present at the Venusian surface[2].

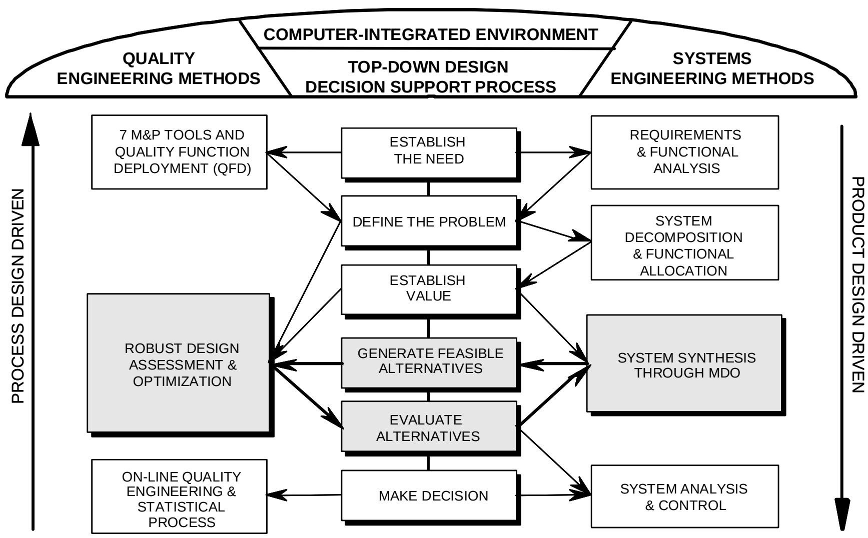


Figure 1. Georgia Tech Generic IPPD Methodology.[1]

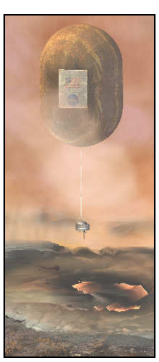


Figure 2. Notional NASA concept for VISE.[5]

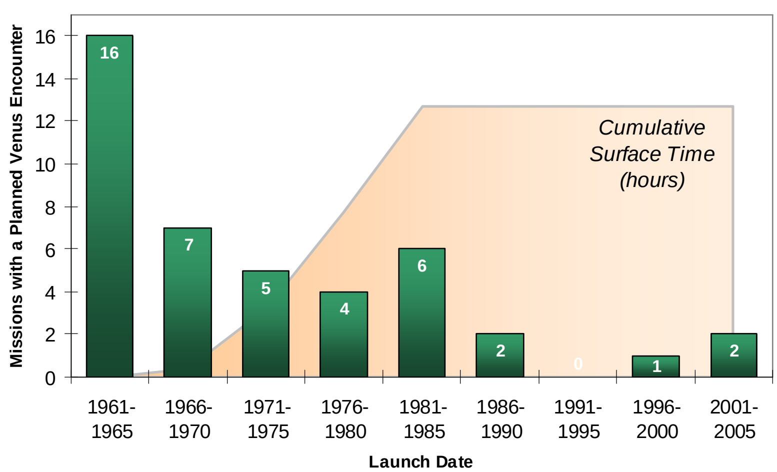


Figure 3. Summary History of Missions with Planned Venus Encounters.[6,7,8]

2. METHODOLOGY SUMMARY

While the generic IPPD methodology shown in Figure 1 encompasses a multitude of different steps which span the gamut of systems analysis activities, for the purposes of initial design decision-making the key parts of this methodology can be condensed into the five shown in the center column of Figure 4. These five steps can be used in series near the initiation of a project to qualitatively convert customer needs into a family of candidate designs for further consideration. This downselection process is methodical and proceeds in a step-by-step by manner, utilizing established quality and systems engineering tools at each step of the way.

It should be noted that this methodology can accommodate quantitative information when it becomes available, and this is discussed in the fifth step. Iterations of the process may also be desirable, for example, if the engineer feels that the knowledge gained from executing the process for a previous iteration may affect the results if a subsequent iteration is completed.

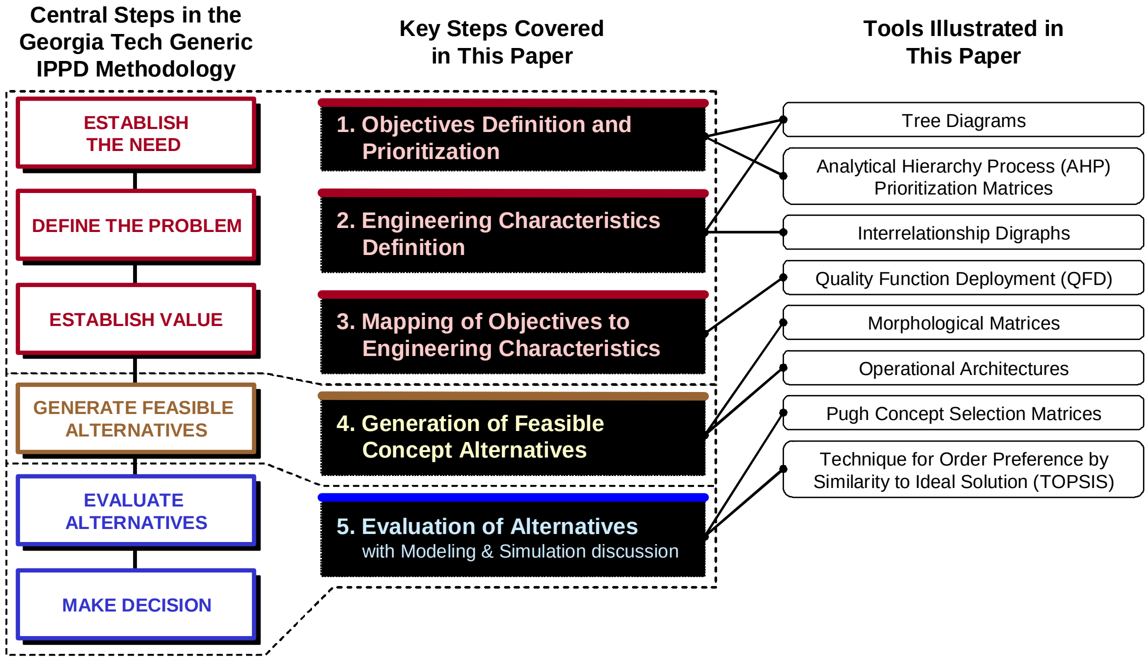


Figure 4. Roadmap of the Georgia Tech Generic IPPD Methodology as illustrated in this paper.

The key steps listed in Figure 4 are next briefly summarized. Following these descriptions, the example application for Venus In Situ Explorer is shown in detail.

1. ***Objectives Definition and Prioritization.*** In this first step, customer objectives are brainstormed with the assistance of a tree diagram, which is one of the Seven Management and Planning Tools developed as a result of post-World War II operations research and Japanese work in total quality control (TQC).[9] This diagram allows brainstormed objectives to be mapped into a hierarchical structure and allow the engineer to select objectives to carry forward to prioritization. This prioritization is accomplished with pairwise comparisons through the Analytic Hierarchy Process (AHP) developed in the 1970s by Thomas Saaty.[10] The result of this step is a set of core objectives and their relative priority weights.

2. ***Engineering Characteristics Definition.*** Next, relevant engineering characteristics are brainstormed, again with the assistance a tree diagram. These engineering characteristics are

intended to represent elements of the design directly controllable by the engineer. Notional targets are defined for each characteristic, and interrelationship digraphs (also part of the Seven Management and Planning Tools) are drawn to identify root causes and key indicators among the different characteristics.

3. ***Mapping of Objectives to Engineering Characteristics.*** This step is key in that it combines the previous two steps into a coherent map showing the correlation of engineering characteristics to customer objectives. Employed here is the Quality Function Deployment (QFD) developed in Japan in the early 1970s and first used on a large scale by the Kobe Shipyard of Mitsubishi Heavy Industries.[11] In many ways the QFD acts as a summary for the entire conceptual design problem, but its primary use here is as a way of qualitatively determining which engineering characteristics are most important for further consideration. While not implemented here, the engineering characteristics from this QFD can be deployed, or mapped, to lower-level objectives in a second QFD. With this in mind, for this illustration, the weightings obtained from the QFD are later used to help define weightings for the fifth step of the process in which candidate designs are evaluated.
4. ***Generation of Feasible Concept Alternatives.*** This next step utilizes a morphological matrix[11] to list discrete options for key design parameters (which can either be engineering characteristics from the previous step or parameters identified through functional or physical decomposition) and translate those options into a total number of potential designs (a number which frequently falls in the millions or billions). In the rare case that a small number of potential designs exists and is manageable, the morphological matrix can be used as a tool to list each combination of options. Tools also exist to interactively view compatibility constraints among options.[12] In this illustration, a standard morphological matrix is be used as a brainstorming tool with which to generate a handful of themed designs to evaluate in the final step.
5. ***Evaluation of Alternatives.*** The final step documented in this paper is a systematic way of qualitatively evaluating the alternative designs generated in the fourth step. While several methods exist in this area, illustrated in detail here are Pugh concept selection matrices[11] and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)[13,14]. For the TOPSIS approach, each alternative design is rated in terms of its performance with respect to each of twelve criteria developed from the engineering characteristics in previous steps. TOPSIS then utilizes weightings for each criterion by drawing on previous steps and determines which designs lie closest to a positive ideal solution and farthest from a negative ideal solution. The Pugh matrices operate in a similar manner but yield coarser results since they do not utilize objective weights and require only relative performance ratings. The output of this step is a series of designs deserving of further consideration. Also discussed briefly is an outline of how physics-based modeling and simulation could be used to add resolution to this step.

3. METHODOLOGY ILLUSTRATION FOR VISE

The following sections are meant to illustrate the steps listed above, specifically for the example of Venus In Situ Explorer (VISE), one of six New-Frontiers-class missions that NASA addresses in the 30-year scope of its 2006 Solar System Exploration Roadmap.

3.1. Objectives Definition and Prioritization

The first part of this first step is the identification of objectives for VISE. To accomplish this, a team brainstormed high-level objectives for the program and arranged them into categories which are described next and visualized via a tree diagram shown in Figure 5.

Previous Venus exploration missions have established a basic description of the conditions prevailing in the atmosphere and at the surface of the planet. However, key scientific questions remain unsolved and many are expressed in terms of scientific objectives:

- ***Surface Analysis*:** Characterization of surface morphology and composition (at multiple sites if possible).
- ***Atmospheric Study*:** Determination of atmospheric composition to further understanding of atmospheric dynamics and the super-rotation mechanism.

The VISE vehicle must also meet challenging technical requirements and attributes:

- ***Mobility*:** Aerial, surface mobility for operations at the surface and in the atmosphere of Venus.
- ***Survivability*:** Autonomy and environmental resistance to survive the mission (against surface temperatures of 730K, pressures of 90 bars, and corrosive atmospheric components).
- ***Communication*:** Need to receive, process, archive and transmit remotely-sensed data to Earth.

Finally, design choices must meet mission and programmatic objectives:

- ***Timely Mission Completion*:** Ability of the intended system to launch and complete its mission within a reasonable schedule and timeframe.
- ***Mission Simplicity*:** Degree to which the system avoids unnecessary complexity, in order to ensure technical feasibility.
- ***Affordability*:** Degree to which VISE returns high value per dollar spent, especially within the constraints of the cost cap imposed by a New Frontiers mission.
- ***Mission Extension Potential*:** Ability to extend the mission beyond the nominal lifetime to yield higher science return.
- ***Technology Demonstration*:** Validation of capabilities important to future missions.

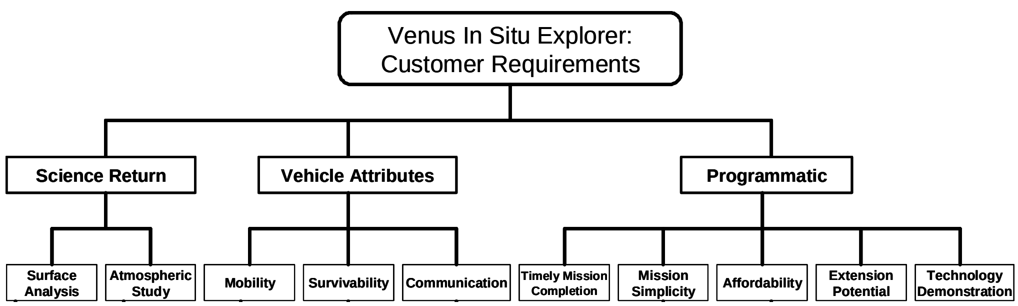


Figure 5. Tree Diagram of Brainstormed Objectives/Customer Requirements.

The ten requirements above could be further decomposed into greater levels of detail; however, this small number allows a concise and complete set of requirements to feed forward for the purposes of this example. Next, the relative importance of the identified customer requirements was determined through the construction of an Analytical Hierarchy Process (AHP) prioritization matrix as show in Table 1. AHP is a systematic way of generating priorities using pairwise comparisons between items rather than requiring the user to select priority weights for all ten items simultaneously. A common AHP scale of 1-9 was used for each comparison to complete the table. For example following along the first row of Table 1, surface analysis was rated slightly more important than atmospheric study (with a rating of 2) but less important than survivability (with a rating of ½).

An important consideration is the consistency of the judgments made by the team (i.e. good agreement between pairwise comparison values, which can be judged because AHP is predicated on a ratio scale), which is defined by a consistency ratio (CR) in Equation 1 below. A perfect prioritization matrix with no inconsistencies has *n* as a maximum eigenvalue, where *n* is the number of requirements. In Equation 1, CI is the consistency index and is as defined in the numerator by λ_{max} and *n*. RI is the random index and is effectively the mean CI which would be found if the matrix were populated randomly; this value is generally precomputed and can be found in published tables[13] (for $n = 10$, RI = 1.49).

$$CR = \frac{CI}{RI} = \frac{\frac{\lambda_{\max} - n}{n-1}}{RI} \leq 0.1 \text{ to be consistent} \tag{1}$$

Applying Equation 1 to the VISE prioritization matrix yields CR = 0.02; since this is well under the recommended CR < 0.1 threshold, this indicates that the prioritization is acceptable. The results of the prioritization are shown in Table 2 showing survivability is the most crucial requirement.

Table 1. VISE Customer Requirements (Objectives) AHP Prioritization Matrix.

	Surface analysis	Atmospheric study	Mobility	Survivability	Com.	Timely completion	Simplicity	Affordability	Tech. Demo.	Extension Potential
Surface analysis	1	2	3	1/2	9	4	2	1	1	6
Atmospheric study	1/2	1	2	1/3	9	3	1	1/2	1/2	4
Mobility	1/3	1/2	1	1/5	4	1	1/2	1/3	1/2	2
Survivability	2	3	5	1	9	6	2	2	3	9
Communication	1/9	1/9	1/4	1/9	1	1/3	1/9	1/9	1/9	1/2
Timely completion	1/4	1/3	1	1/6	3	1	1/3	1/4	1/3	2
Simplicity	1/2	1	2	1/2	9	3	1	1/2	1	5
Affordability	1	2	3	1/2	9	4	2	1	1	7
Tech. Demo.	1	2	2	1/3	9	3	1	1	1	5
Extension Potential	1/6	1/4	1/2	1/9	2	1/2	1/5	1/7	1/5	1

Table 2. AHP Prioritization Matrix Ranking Results.

Criteria	Score	Rank
Surface Analysis	0.149	3
Atmospheric Study	0.093	6
Mobility	0.050	7
Survivability	0.248	1
Communication	0.015	10
Timely Completion	0.040	8
Simplicity	0.105	5
Affordability	0.152	2
Tech. Demo.	0.124	4
Extension potential	0.024	9

3.2. Engineering Characteristics Definition

Next, basic engineering characteristics are brainstormed and categorized through a tree diagram as shown in Figure 6. The highest-level categories in the tree diagram are Programmatic, Mission Profile, and Hardware Characteristics. Programmatic characteristics include considerations such as cost, risk and launch date. The Mission Profile category is resolved in terms of the baseline mission timeline and the flexibility and mobility offered by a particular mission profile. Finally, the hardware characteristics include physical characteristics of the vehicle such as mass, power, achievable data rate, and number of vehicles in the overall VISE architecture.

Because engineering characteristics are coupled to each other, there is a need to describe their interactions, a set of information which will be used later in the QFD.[‡] In Figure 7, two interrelationship digraphs show key indicators (which are the characteristics most driven by other characteristics) and root causes (which are characteristics which drive the largest number of other characteristics). Risk and data

[‡] It is worth noting that, although it was not done in this project, interactions may also be identified among the objectives if this insight is desired. A section of the QFD not used in this project is designed to accommodate this information.

rate appear to be the main key indicators while the main root cause is the number of vehicles, although it can be seen that this root cause is only somewhat more important than several other characteristics such as power consumption, mass, surface time per visit, and number of surface visits.

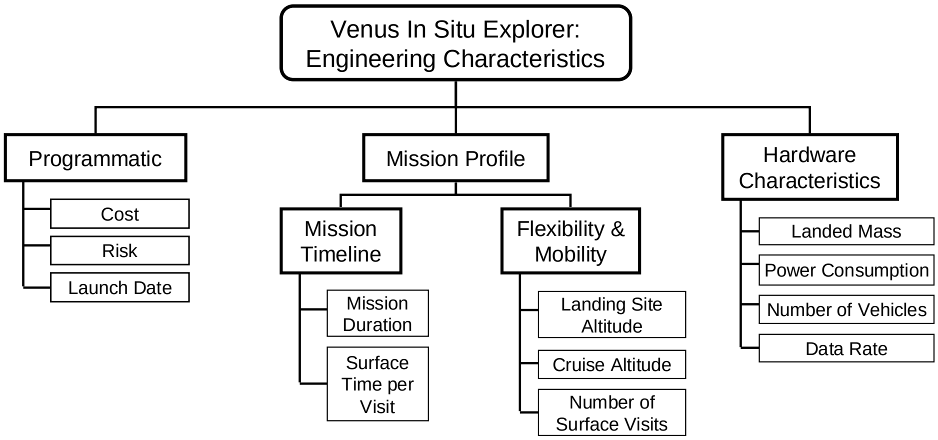
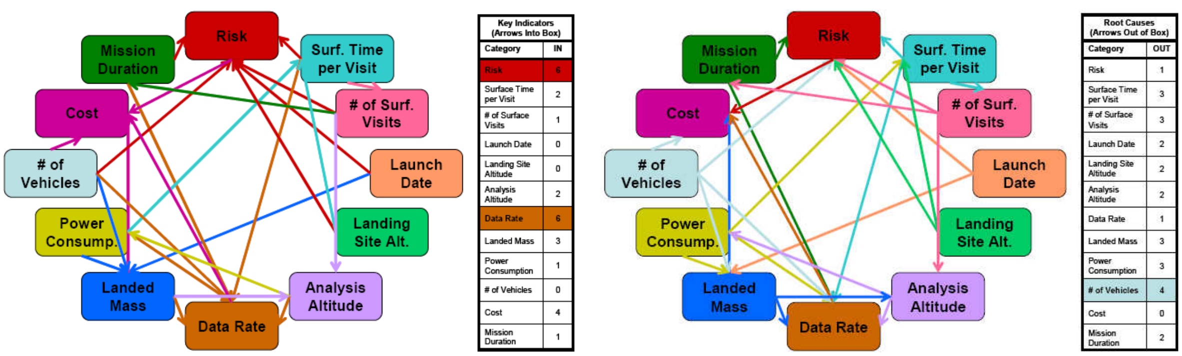


Figure 6. Tree Diagram of Brainstormed Engineering Characteristics.



Key Indicators (Arrows Into Box)	
Category	IN
Risk	6
Surface Time per Visit	2
# of Surface Visits	1
Launch Date	0
Landing Site Altitude	0
Analysis Altitude	2
Data Rate	6
Landed Mass	3
Power Consumption	1
# of Vehicles	0
Cost	4
Mission Duration	1

Root Causes (Arrows Out of Box)	
Category	OUT
Risk	1
Surface Time per Visit	3
# of Surface Visits	3
Launch Date	2
Landing Site Altitude	2
Analysis Altitude	2
Data Rate	1
Landed Mass	3
Power Consumption	3
# of Vehicles	4
Cost	0
Mission Duration	2

Figure 7. Interrelationship Digraphs showing Key Indicators (left) and Root Causes (right).

The final important part of this step is the identification of approximate targets for these engineering characteristics so that a better context is defined for the problem. In the programmatic category, the total cost target is approximately $700 million which is on par with a NASA New Frontiers mission budget[§]. Target risk is qualified as medium at this point, and the launch date target is set at 2013 based on the earliest reported launch opportunity in the literature.[4]

In terms of the category of mission profile, mission duration is targeted at 90 days (measured as time from VISE atmospheric entry) to help qualify technologies for the follow-on Venus Surface Explorer (VSE) mission, which targets surface operations for 90 days.[4] Harsh conditions also limit the surface time per visit, which is ambitiously targeted at 4 hours, roughly twice any previous mission's surface duration. The target value on number of surface visits is set to six. Combined with surface time per visit, a total of 24 hours would be tallied on the surface of Venus. However, depending on the concept selected to allow a lander to ascend from the surface and later descend to another location, this target may be very difficult to meet and may require revision in any future iterations. In terms of landing altitude, the target is set to

[§] The NF-3 Program Announcement, which was released after this work was completed, has set a cost cap of $650 million (in FY09 dollars), excluding launch vehicle.[3]

1.5 km above mean surface level which still allows surface inspection to be carried over continent-sized regions but avoids the higher temperatures and pressures at lower altitudes. The cruise altitude is chosen at 55 km based on the atmosphere temperature and density profiles to ensure Earth-like conditions for the operation of VISE over most of its lifetime (with the exception of surface excursions).

Finally, in terms of hardware characteristics, the VISE landed mass target is set at 200 kg, which is in the same class as the Mars Exploration Rovers. The rationale is that similar instruments would be required for the VISE mission and that the mass for increased structural loads on VISE would be somewhat offset by the mass of the MER mobility system which would not be required for VISE. The overall power consumption is targeted at 100 W, slightly low compared to the Mars Exploration Rover mission class in order to limit the internal heat generation. A maximum data rate target of 10 kbps is selected based on the team member previous experience in interplanetary link design. The number of vehicles is not predetermined in the study and is treated as a variable with which to optimize the design because various architectural options are to be considered in future steps.

3.3. Mapping of Objectives to Engineering Characteristics

In this third step, objectives and engineering characteristics are compiled into a quality function deployment (QFD), a means of mapping the stakeholders' objectives to the technical requirements. The result, shown in Figure 8, integrates the voices of the engineer and customer. On the left-hand side, the customer's input is compiled into a list of requirements, each with a relative value of importance. Engineers contribute a list of characteristics (shown at the top of the figure) that can satisfy the customer's requirements. Note that the objectives, objective priorities, and engineering characteristics in the QFD are identical to those from the first and second steps of this process. The roof of the QFD contains the correlation matrix, showing the nature and degree of the engineering characteristics' interdependence. Here, pound signs, empty circles, and bullseye circles indicate strong negative, positive, and strong positive relationships, respectively. Note that the correlation matrix is derived from the interrelationship digraph from the second step of this process. The targets discussed earlier are shown just below the central relationship matrix of the QFD.

The QFD was filled out by the team in an interactive meeting. The relationship matrix in the middle of Figure 8 relates customer requirements to engineering characteristics, marking weak correlations with triangles, moderate correlations with circles, and strong correlations with bullseye circles; each symbol have corresponding values of 1, 3, and 9, respectively. Organizational difficulty values, again using the 1-3-9 scale, are multiplicative factors applied to each engineering characteristic (1 denoting low difficulty and 9 meaning high) based on the perceived difficulty of meeting the target value.

The weighted importance row of the QFD contains the scalar product of the customer importance values and relationship matrix values. Relative importance is calculated by dividing each weighted importance value by the sum of all of the weighted importance values, resulting in a scaled bar graph. The difficulty-weighted importance is the product of each weighted importance value and the associated organizational difficulty. The final line in the QFD figure is the relative comparisons of the difficulty-weighted importance values.

Note that the relative importance row of the QFD indicates that three engineering characteristics require primary attention during design: risk, cost and surface time per visit. Note, however, that when the difficulty factors are applied, surface time per visit and number of surface visits rise to the position of most important. This suggests that although number of surface visits is not of top relevance in attaining customer objectives, the set target is difficult to achieve (and may be a good candidate target to relax in a later iteration). As will be discussed later, these QFD weights assist in determining weights for concept evaluations in TOPSIS.

One final note is that the QFD can also provide information on which engineering characteristics can be neglected as drivers at this early stage of design. Note that for VISE, the concern about landed mass is almost negligible, which is very different than for robotic missions to Earth's other neighbor of Mars. In the case of Venus, the very thick atmosphere allows a relatively easy landing for a large range of masses. Additionally, note that of little concern are the characteristics of launch date (nearly identical launch opportunities occur approximately every 19 months) and data rate (communications from the surface of Venus have occurred in the past, and long cruise periods at a high altitude will allow VISE to transmit the bulk of data at altitudes with less atmospheric attenuation).

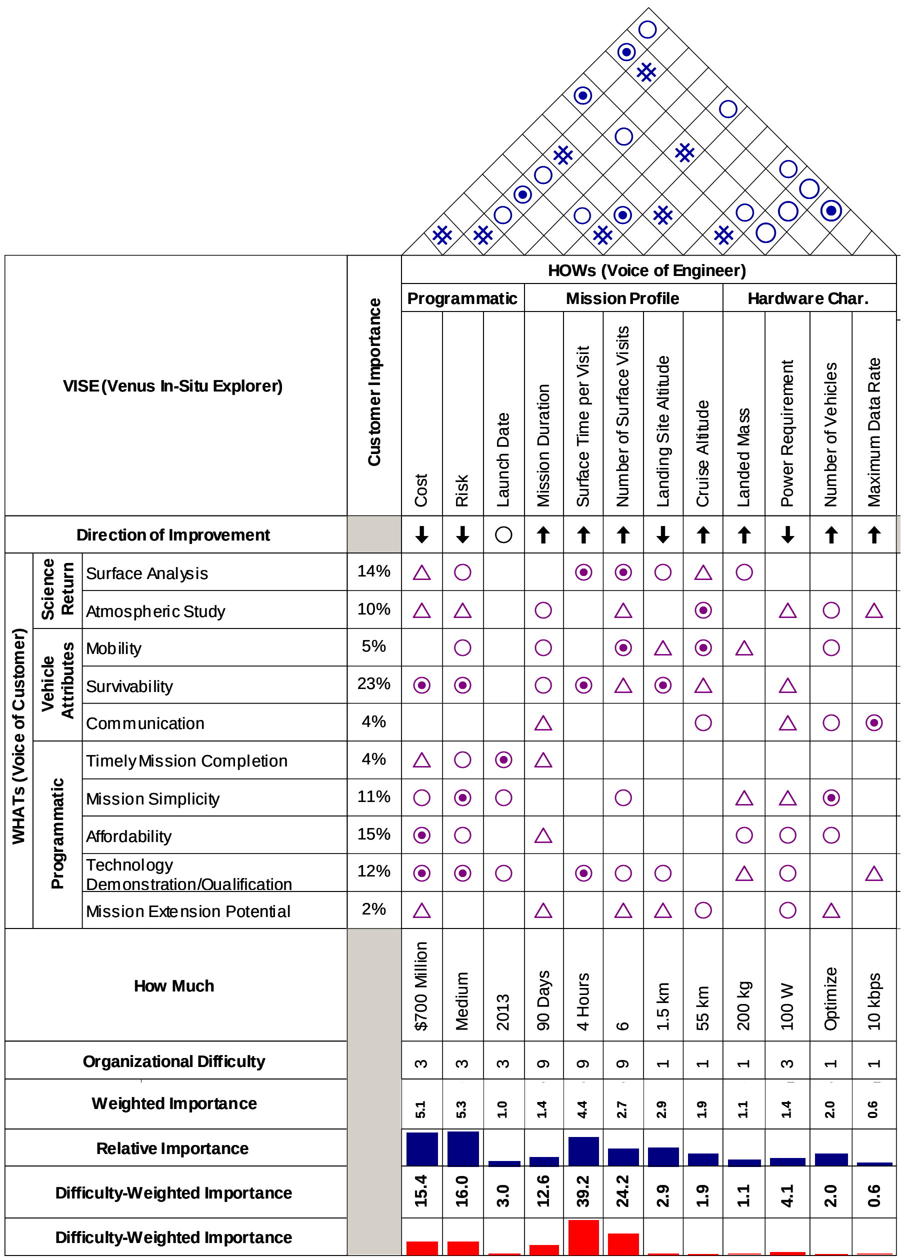


Figure 8. Quality Function Deployment (QFD) for VISE.

3.4. Generation of Feasible Concept Alternatives

Once the design problem has been clearly defined and understood, potential solution concepts must be developed. A morphological matrix aids the development of new design concepts that might not ordinarily be considered. The matrix depicts the system functions and subfunctions in a logical order. Design teams then brainstorm possible ways of fulfilling each function, quickly resulting in a large numbers of possible system combinations. The morphological matrix for VISE (shown in Table 3 below) contains 12,441,600,000 possible combinations. Before evaluation methods are applied, it may often be helpful to highlight unreasonable alternatives in the morph matrix (as the red highlights indicate in Table 3) to limit the scope of the trade space. Design configurations are then developed from the morph matrix.

The first part in this step of the VISE process is the generation of the morphological matrix itself. The VISE matrix shown below has 19 rows broken down into Structure/Configuration and Mission options. These 19 options are based on functional and physical decompositions of the VISE spacecraft and mission, although this is not the only way of determining the options of the morphological matrix (another possibility, for example, would be to use the engineering characteristics identified in previous steps). For VISE, a physical decomposition yields options for spacecraft characteristics such as data relay, power source, thermal control methods, structure, and landing methods. Also in this category are high-level architectural options such as lander platform and number of vehicles. A functional decomposition yields options in terms of launch, interplanetary transfer, orbit insertion (if applicable), entry, descent, and landing (EDL), and science measurements.

With the rows of the morphological matrix defined, the columns then represent alternatives in the category of each row. For example, the lander platform may take on the form of a balloon (an alternative often used in Venus atmospheric mission studies) but may also be an airship, airplane, helicopter, or rigid-bellows device (due to the high density at low altitudes on Venus, a metal bellows may suffice instead of a balloon), among other options. Thus, a morphological matrix allows the engineer to define a design by selecting one alternative from each row. In an ideal case, selections in one row are independent of selections from other rows, although since rarely is this strictly true for complex systems, more advanced tools exist to assist the engineer in understanding interactions within the matrix.[12]

From the morphological matrix presented above, six themed concepts for VISE were extracted.[**] A detailed description of each is presented in the table below and in the following paragraphs.

- ***Traditional Concept.*** The traditional concept emulates typical NASA missions. A single lander relays communication through a single orbiter. Power is provided by solar cells. The balloon for the cruise stage is inflated using a consumable supply of gas (such as helium). Thermal control is managed passively with phase change materials and by vacuum-insulating the critical components. EDL is carried out by a combination of parachutes and utilization of the buoyancy of the vehicle in Venus' dense atmosphere. A concept description sheet (CDS) for this concept can be seen in Figure 9, and the morphological matrix option selections for this concept are highlighted in yellow in Table 3.

[**] Ideally, the morphological matrix would allow one to enumerate all possible design concepts. However, very often this number is much too large to be practical (for example, analyzing 12.4 billion designs for VISE would take nearly 400 years, optimistically assuming a computer could analyze one design per second). Instead, concepts can be selected according to themes, which is the method used here.

Table 3. Morphological Matrix for VISE. Red squares indicate alternatives which can be reasonably eliminated. Yellow squares indicate characteristic selections for the Traditional Concept discussed below.

Characteristics	Alternatives 1	2	3	4	5	6	7	8	9	No. of Opt.'s
1. Structure/Configuration										
1.1 Lander Configuration										
1.1.1 Data Relay	Direct from Surface	Relay After Ascent	Relay via Orbiter							3
1.1.2 Lander Platform	Propulsive	Rigid Bellows	Mechanical	Venus Aeroplane	Helicopter	Balloon – Skimmer	Balloon – Gas Pump	Balloon – Consumable Gas	Airship	9
1.1.3 Battery Supplement	Solar Panel	Fuel Cell	Traditional RTG	ASRG	Venus In-situ					5
1.1.4 Active TCS	Cryocooler	Heat Concentrator	CO_2 Phase Change	Other Phase Change	None					5
1.1.5 Passive TCS	Vacuum Isolation	Aerogel								2
1.1.6 Landing Gear	Conventional	Wheels	Crushable	Inflatable	None					5
1.2 Structure Material	Aluminum	Titanium	Composites							3
1.3 Vehicle Split	Lander Only	Lander and Orbiter								2
1.3.1 Number of Landers	1	2	3	4						4
1.3.2 Number of Orbiters	0	1	2	3	4					5
2. Mission										
2.1 Earth Departure										
2.1.1 Launch System	Atlas	Delta	Ariane	Russian						4
2.1.2 Type of Transfer	Spiral	Direct Insertion	Lower Energy Transfer							3
2.1.3 Direct to Venus	Yes	No								2
2.2 Venus ED&L Methods	Buoyancy	Propulsive	Parachutes	Combination	Other					5
2.3 Venus Orbit Insertion (Orbiter)	Aerocapture	Propulsive	Combination	Aerobraking						4
2.4 Science										
2.4.1 Surface Study										
2.4.1.1 Composition	Yes	No								2
2.4.1.2 Seismometry	Yes	No								2
2.4.1.3 Mapping	Yes	No								2
2.4.2 Atmospheric Study										
2.4.2.1 Composition	Yes	No								2
2.4.2.2 Dynamics	Yes	No								2
					No. of Combinations			12,441,600,000		

- ***Low-Cost Concept.*** The low-cost concept uses only one lander without an orbiter. Data is stored and then transmitted directly to Earth at high altitudes. Solar power generation is chosen for simplicity. A balloon concept is proposed. Parachutes are used for EDL. To minimize cost, a Russian launch vehicle is used. To reduce the propellant needed for interplanetary cruise and insertion, a low-energy transfer and a direct entry are considered. The only scientific objective of the mission is the determination of surface composition.

- ***Revolutionary Concept.*** The Revolutionary concept employs two vehicles to survey Venus from orbit and three airplanes. An advanced SRG is used for power. A low-thrust spiral trajectory is used to mitigate mass limitations which will likely be imposed by the amount of hardware on this mission. Aerocapture is used to insert into Venus orbit. All aspects of Venus science are studied, from surface composition to seismometry, mapping, atmospheric composition, and atmospheric dynamics.

- ***Evolutionary Concept.*** The Evolutionary concept takes a more measured approach to including new technologies, but attempts to include options that will be most helpful in future missions. Orbit insertion is accomplished by aerobraking, like many of the recent Mars missions. Surface science capability is maximized by using two landers. The landers relay communications through a single orbiter. Traditional RTGs provide power for the landers, and both active and passive thermal control are employed. The landers use an inflatable balloon to partially ascend for cooling and communications purposes. The structures are composite wherever possible, and titanium otherwise.

- ***Advanced Concept.*** The Advanced concept is similar to the Evolutionary one except that it uses a rigid bellows (metallic balloon). A rigid bellows can fly because of the high density of Venus's atmosphere. However, since it is heavier than classical balloons, it has lower altitude capability and cannot get to as high of an altitude to cool down. Therefore, a more advanced thermal control system (heat concentrator) is employed.
- ***Distributed Concept.*** The philosophy behind the Distributed concept is to use four landers to maximize surface data return. Each lander is similar to the lander in the Traditional concept, and data would be relayed through an orbiting vehicle. However, unlike the Traditional concept, aerobraking is employed instead of a propulsive orbit insertion.

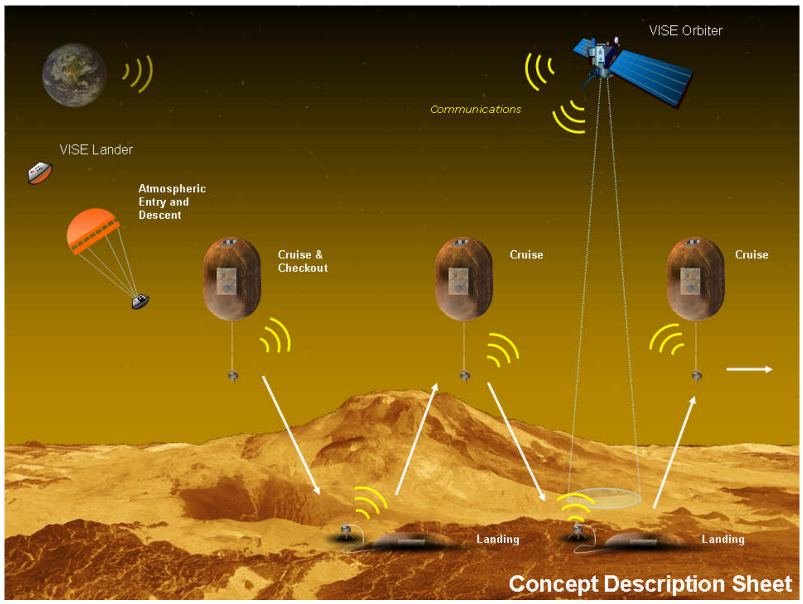


Figure 9. Traditional Concept CDS.

3.5. Evaluation of Alternatives

In this final step, the six concepts presented above are evaluated via two decision-making tools, the Pugh selection matrix and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). These results are then used to draw conclusions regarding the feasibility of each concept and which should be pursued for further investigation.

3.5.1. Pugh Concept Selection Matrices

One helpful decision tool at the concept stage is the Pugh selection process[11] (see Figure 10). It allows a comparison of several design concepts against an established datum and ranks those concepts with respect to design criteria. For this illustration, the criteria are obtained from the engineering characteristics of the QFD. In the matrix, a "+" sign shows that a concept is superior to the standard, a "-" shows that it is worse, and an "S" shows they are the same. The concept with the greatest positive difference between the sum of plusses and the sum of minuses is taken to be the best concept. This process is repeated several times with different datum designs to guarantee consistency in the results. The datum of a given matrix is taken to be the best current concept from the matrix at the previous iteration.

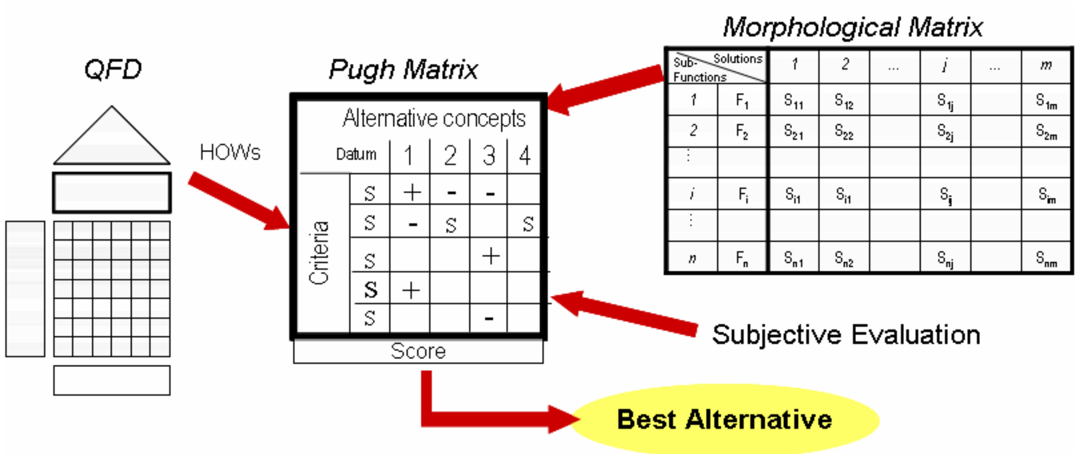


Figure 10. Pugh Selection Process Graphical Summary

This procedure was applied for the VISE mission in a team setting. First, the Venera 13 mission was set as the datum reference mission and a Pugh concept selection matrix was populated. In this iteration, the Traditional concept was scored the highest. Next, this highest-scoring concept was selected for the datum and the matrix was repopulated using team input. Examination of the resulting Pugh matrix shows that Traditional, Revolutionary and Advanced concepts cannot be distinguished, and that Distributed is a superior concept.

While this method is not necessarily convincing as a stand-alone tool since (it does not incorporate weights on criteria or within the matrix ratings), it can serve as a useful tool in identifying trends and preparing the engineering team for using TOPSIS. The Pugh matrix also has some advantage since it can be populated with a limited amount of data since only qualitative analysis is required.

Best concept

	Concept 1 *Traditional*	Concept 2 *Low-Cost*	Concept 3 *Revolutionary*	Concept 4 *Evolutionary*	Concept 5 *Advanced*	Concept 6 *Distributed*
Cost		+	-	-	-	-
Risk		-	-	S	-	+
Launch Date		+	-	-	-	-
Mission duration		-	+	+	S	S
Surface time / visit	D	-	+	-	+	S
# of Surface Visits	A	+	+	+	+	S
Landing Site Alt.	T	-	-	-	S	S
Cruise Altitude	U	-	-	S	-	S
Landed Mass	M	-	+	+	S	+
Power Requirement		+	-	-	-	S
# of Vehicles		-	+	+	S	+
Max. Data Rate		-	+	+	-	+
Score		-4	0	0	-4	2

Figure 11. Second-Iteration Pugh Matrix for VISE Concept Comparison

3.5.2. Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)[13,14] operates by transforming a set of alternatives and weights for *n* objective criteria into a problem in an *n*-dimensional Euclidean space. Two points, the positive and negative ideal points, are defined as shown in Figure 12 as the combination of the best and worst occurrences of objective values in the data set. TOPSIS then computes the Euclidean distance from each alternative design to the positive and negative ideal designs and searches for designs which are close to the positive ideal design and far from the negative ideal design. TOPSIS can accommodate both qualitative and quantitative data (for example, if cost is an objective and can be computed, the exact cost number can be used as a metric within TOPSIS; alternatively, if only a qualitative rating is available, that can be converted to a number on a rating scale and used in place of the exact cost estimate) but requires weights for objectives.

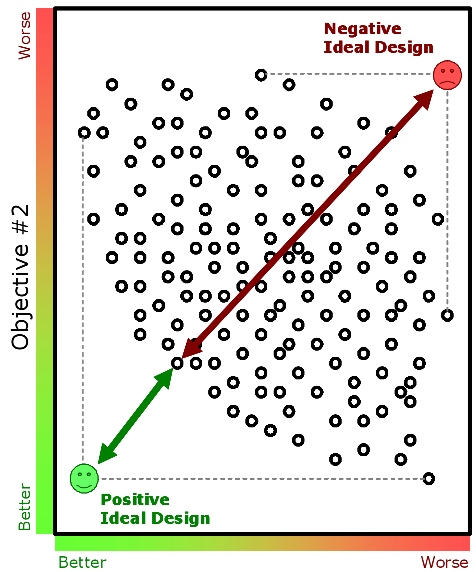


Figure 12. Illustration of TOPSIS for a two-objective problem. Black circles indicate candidate designs, and arrows indicate distances from ideal designs.

The method of TOPSIS can be divided in a series of steps:

1. ***Obtain performance for the different alternatives over the selected criteria.*** Unlike the qualitative Pugh process which only required a user to distinguish between better/worse/same ratings, numeric performance ratings must be provided for TOPSIS. For VISE, a data matrix was filled using estimates of engineering characteristic values for each concept based on previous missions and an extensive literature search (see Table 4).

Table 4. TOPSIS Data Matrix for VISE.

	Concept 1 Traditional	Concept 2 Low-Cost	Concept 3 Revolutionary	Concept 4 Evolutionary	Concept 5 Advanced	Concept 6 Distributed
Cost	600	350	1500	700	850	750
Risk	5	9	8	6	6	3
Launch Date	1	1.3	0.85	0.9	0.95	0.9
Mission Duration	90	90	110	105	100	90
Surface Time per visit	4	2	6	4	6	4
Number of Surface Visits	6	6	8	6	6	6
Landing Site Altitude	1.5	2	0.5	1	1	1
Cruise Altitude	55	40	60	55	55	55
Landed Mass	200	200	400	300	200	600
Power Requirement	100	75	600	100	400	600
Number of Vehicles	2	1	5	3	2	5
Maximum Data Rate	30	15	65	40	30	65

2. ***Develop a set of importance weights for each of the criteria.*** In this study, the TOPSIS weights are taken as the arithmetic average of three different weighting schemes. The first scheme is a normalized unweighted importance directly from the QFD. The second scheme is the normalized weighted importance directly from the QFD (i.e. the unweighted importance multiplied by the difficulty factor). The third scheme is a prioritization using Analytical Hierarchy Process (AHP). Unlike the results found in the QFD which are based on indirect rankings via customer priorities, in the AHP the engineering characteristics are directly compared to each other (although they do

not directly account for customer priorities). Shown in Figure 13 is the average of the weightings produced by these three methods taken to reduce the effect of bias introduced by any single method. Note that risk and cost are of the highest importance, followed closely by surface time per visit. The number of surface visits achieved is the next most important, followed closely by mission duration.

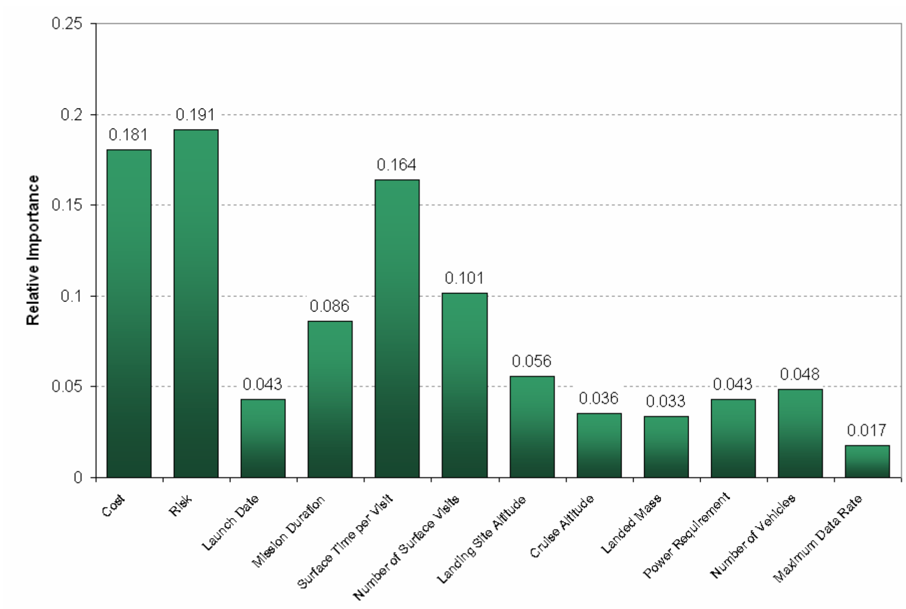


Figure 13. TOPSIS Criteria Weights used for VISE.

3. ***Rank alternatives by determining the relative closeness from ideal solution.*** The attributes are then listed into benefit (+) or penalty (-). An ideal positive and an ideal negative solution are evaluated by maximizing the benefits and the penalties respectively within the pool of values given in the data matrix. To indicate how far a concept lies from the ideal solutions, the relative closeness defined in Equation 2 below is calculated. In Equation 2, x_i is the value of engineering characteristic i in the weighted normalized space, and $x_i^{\pm}$ is the value of engineering characteristic i for the positive/negative ideal solution in the weighted normalized space.

$$C = \frac{S^-}{S^- + S^+} \quad \text{where } S^{\pm} = \sqrt{\sum_{i=1}^{12} \left(x_i^{\pm} - x_i\right)^2} \qquad (2)$$

Table 5 provides the score for all concepts. Distributed concept receives the highest score, and Traditional, Advanced and Evolutionary concepts are closely behind. On the other hand, Low-Cost and Revolutionary are clearly far behind and should be removed from the set of alternatives to be considered further in later phases. It is interesting to note that this ranking is consistent with the one found by the Pugh method.

Table 5. VISE concept ranking via TOPSIS.

	Concept 1 Traditional	*Concept 2* Low-Cost	*Concept 3* Revolutionary	*Concept 4* Evolutionary	*Concept 5* Advanced	*Concept 6* Distributed
C	0.53	0.38	0.40	0.50	0.53	0.66
Rank	**2**	**6**	**5**	**4**	**2**	**1**

3.5.3. Potential Extension to Modeling and Simulation

Importantly, it was concluded from the steps above that, while two concepts could be easily eliminated (the Low-Cost and Revolutionary) via the qualitative methods used, four remained which could not be easily distinguished (Advanced, Evolutionary, Distributed, and Traditional). These four concepts require quantitative data to back up any definitive ratings of their suitability, but it would not be large leap to envision replacing the current values in Table 4 with values calculated using physics-based system sizing and synthesis models (such as FLOPS[16] and POST[17] used within NASA in the air and space design fields, respectively). With such models, it would also be possible to consider parametric trade studies as well as potentially model concept alternatives not considered in the first iteration of the process illustrated here.

Figure 14 shows a notional framework for implementing such a sizing and synthesis model. Prime components include a Lander Model, Entry System Model, Orbiter/Cruise Stage Model, and Mission Model. Dashed lines are drawn to indicate links between models and the flow of information. For example, launch and arrival dates for the mission will define the interplanetary transfer trajectory and partially determine the atmospheric entry state plus any insertion burn ΔV for an orbiter. In turn, the entry state will define (via trajectory simulation) the loads and heating on the entry vehicle, and the insertion ΔV will define the amount of propellant required by an orbiter. The sizing of vehicle systems leads to mass and power estimates, which are inputs into a cost and risk model.

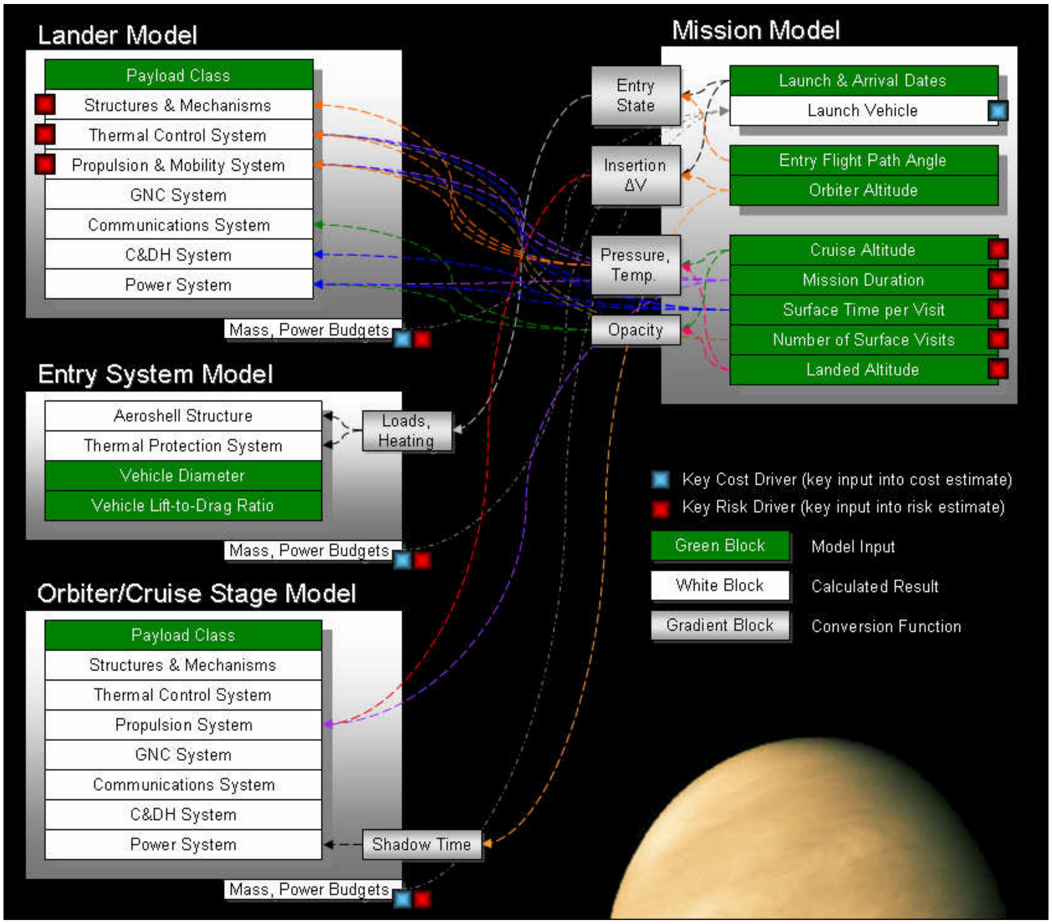


Figure 14. Notional VISE Vehicle and Mission Modeling Framework.

4. CONCLUSION

This paper has provided an illustration of how the Georgia Tech generic IPPD methodology and its associated tools may be systematically applied to the initial stages of design for an interplanetary robotic mission. Through the example of Venus In Situ Explorer, five steps have provided a flow to follow during the earliest qualitative stages of design. In the first step, objectives for the program were concisely defined and prioritized using tree diagrams and AHP pairwise comparisons. Next, engineering characteristics and their interrelationships were defined through tree diagrams and interrelationship digraphs. In the third step, these engineering characteristics were combined with the program objectives in the form of a QFD which yielded information on the relative importances of characteristics with respect to the design. In the fourth step, potential designs were brainstormed with the assistance of a morphological matrix. In the final step, these potential designs were evaluated with Pugh concept selection matrices and TOPSIS using weights generated in earlier steps. A prime output of the process is a set of designs suitable to carry forward for further consideration.

It is important to note that the illustration here for Venus In Situ Explorer was only a first iteration through the process and, as with all design problems, the team's knowledge about the problem at the end of the process was far greater than at the beginning. As a result, a second iteration (and potentially more) would certainly be warranted for a funded flight project, for example. Also, in a second iteration, the team might decide to modify the implementation of the process in terms of step-to-step linkages. For example, it may be possible to carry top-level objectives through all five steps such that they become the objectives against which alternative designs are rated in the fifth step. It also may be possible to use the engineering characteristics from the second step as the rows of the morphological matrix instead of a separate functional or physical decomposition.

Overall, the methodology outlined by this paper provides a framework and several tools useful for undertaking the problem of designing a complex engineering system. Applicability to space exploration has been demonstrated, and it is hoped that this methodology will find a place in the future of interplanetary robotic probe design projects.

5. ACKNOWLEDGEMENTS

The student authors of this paper have formed an eclectic team drawn from four separate research organizations affiliated with Georgia Tech and one NASA center. As such, the authors would like to recognize the Space Systems Design Laboratory led by Dr. Robert Braun, the Aerospace Systems Design Laboratory led by Dr. Dimitri Mavris, the Combustion Laboratory led by Dr. Ben Zinn, the National Institute of Aerospace and Dr. Alan Wilhite, and NASA Johnson Space Center.

6. REFERENCES

[1] Schrage, D.P. "Technology for Rotorcraft Affordability Through Integrated Product/Process Development (IPPD)." Nikolsky Lecture Paper. American Helicopter Society 55th Annual Forum, Montreal, 25-29 May 1999.

[2] 2006 Solar System Exploration Roadmap. NASA Science Mission Directorate. Sept. 2006. Available: http://solarsystem.nasa.gov/multimedia/downloads/SSE_RoadMap_2006_Report_FC-A_med.pdf [4 Oct. 2007].

[3] "New Frontiers Program Announcement." NASA New Frontiers Program. 14 May 2008. Available: http://discoverynewfrontiers.nasa.gov/news/New%20Frontiers/2008/news_051408.html [8 June 2008].

[4] "Focus Group: Planetary Formation and Evolution." NASA Venus Exploration Analysis Group. Available: http://www.lpi.usra.edu/vexag/Nov2005/Mackwell.pdf [14 June 2008].
[5] "New Frontiers Program Description." NASA New Frontiers Program. Available: http://newfrontiers.nasa.gov/program_plan.html [8 June 2008].
[6] "Chronology of Venus Exploration." National Space Science Data Center. 20 Nov. 2007. Available: http://nssdc.gsfc.nasa.gov/planetary/chronology_venus.html [8 June 2008].
[7] NASA Goddard Space Flight Center, National Space Science Data Center Spacecraft Query [online database]. Available: http://nssdc.gsfc.nasa.gov/database/sc-query.html [25 July 2007].
[8] NASA Solar System Exploration, Solar System Exploration Missions [online database]. Available: http://solarsystem.nasa.gov/missions/index.cfm [8 June 2008].
[9] Brassard, M. *The Memory Jogger Plus+ Featuring the Seven Management and Planning Tools*, GOAL/QPC, 1989.
[10] Saaty, T.L. *The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation*, McGraw-Hill, New York, 1980.
[11] Dieter, G.E. *Engineering Design*. 3rd ed., McGraw-Hill, Boston, 2000.
[12] Engler, W., Biltgen, P., and Mavris, D. "Concept Selection Using an Interactive Reconfigurable Matrix of Alternatives (IRMA)." AIAA 2007-1194. 45th AIAA Aerospace Sciences Meeting and Exhibit, Reno, 8-11 Jan. 2007.
[13] Lai, Y., Liu, T., and Hwang, C. "TOPSIS for MODM." *European Journal for Operational Research*, Vol. 76, 1994.
[14] Hwang, C.L. and Yoon, K. *Multiple Attribute Decision Making: Methods and Applications*, Springer-Verlag, Heidelberg, 1981.
[15] Alonso, J.A. and Lamata, M.T. "Consistency in the Analytic Hierarchy Process: A New Approach." *International Journal of Uncertainty, Fuzziness and Knowledge-Based Systems*, Vol. 14, No. 4. 2006.
[16] McCullers, L.A. "Aircraft Configuration Optimization Including Optimized Flight Profiles, Multidisciplinary Analysis and Optimization, Part I." NASA CP-2327, 1984.
[17] Brauer, G.L., Cornick, D.E., and Stevenson, R. "Capabilities and Applications of the Program to Optimize Simulated Trajectories (POST): Program Summary Document." NASA CR-2770, 1977.