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A Software Tool Suite for Small Satellite Risk Management

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A Software Tool Suite for Small Satellite Risk Management

by

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A Software Tool Suite for Small Satellite Risk Management

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Risk management plans improve the likelihood of mission success by identifying potential failures early and planning mitigation methods to circumvent any issues. However, in the aerospace industry to date, risk management plans have typically only been used for larger and more expensive satellites, and have rarely been applied to satellites in the shape of 10 x 10 x 10 centimeter cubes, called CubeSats. Furthermore, existing risk management plans typically require experienced personnel and significant time to run the analysis. The purpose of this research was to develop two risk management software tools, the CubeSat Risk Analysis tool and the CubeSat Decision Advisor tool, which could be used by anyone with any level of experience. Moreover, the tools simply require the user to enter their mission-specific data; the software tools calculate the required analysis.

The CubeSat Risk Analysis tool was developed for the purpose of reducing the subjectivity associated with estimating the likelihood and consequence of spacecraft mission risks. The tool estimates mission risk in terms of input characteristics, such as satellite form factor, mass, and development cycle. Using a historical database of small satellite missions, which was gathered in the course of this research, the software determines the mission risk root causes which are of the highest concern for the given mission.

The CubeSat Decision Advisor tool uses components of decision theory such as decision trees, multi-attribute utility theory, and utility elicitation methods to determine the expected utility of a mitigation technique alternative. Based on the user's value preference system, assessment of success probabilities, and resources required for a given mitigation technique, the tool suggests the course of action which will normatively yield the most value for the cost, personnel, and time resources required.

The goals of this research were met in the development of two easily-accessible and free risk management software tools to assist in university satellite mission development. But more importantly, these tools will reach beyond the academic setting and allow small satellites to continue to evolve as a platform to accomplish educational, scientific, and military objectives.

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Chapter 1: Introduction

According to the NASA Risk Management Procedural Requirements[1], “risk is the potential for performance shortfalls, which may be realized in the future with respect to achieving explicitly established and stated performance requirements.” These potential shortfalls range from lack of the needed institutional support for the mission to the areas of safety, technical, cost and schedule of the project.

Based on this concept, risk management is the process of risk identification, analysis, mitigation planning and tracking of the root cause of problems and their ultimate consequences. Risk management plans improve the likelihood of mission success by identifying potential failures early and planning methods to circumvent any issues. However, in the aerospace industry to date, risk management plans have typically only been used for larger and more expensive satellites, and have rarely been applied to smaller satellites with a mass less than 10 kg, called nanosatellites. For this class of smaller satellites, which is becoming of greater interest to the aerospace industry, these larger-scale risk management plans need to be adapted to provide a suitable risk management methodology for nanosatellites. A new set of practices is needed that is appropriate to the schedule, budget, and risk tolerance of this emerging class of satellites. Defining a method for applying risk management to nanosatellite projects will result in more informed decision making, ultimately producing more successful spacecraft missions. It is timely to perform this research now, as this satellite class range continues to grow in use and importance.

This research focuses on the development of two software tools to be used for risk management of small satellites. The CubeSat Risk Analysis tool is specific to the CubeSat platform, but the CubeSat Decision Advisor is applicable to any size spacecraft.

These tools use risk analysis, regression methods, and decision analysis theory to guide users through the risk management process that is typical of spacecraft missions. These tools are particularly useful to low-cost missions, or missions staffed by personnel with little experience. No tools specific to small spacecraft missions existed prior to this research, and so the impact of this research is largely due to the software tool innovations to be described in the coming chapters.

1.1 RISK MANAGEMENT AND DECISION MAKING IN THE AEROSPACE INDUSTRY

A risk management plan entails three major steps which each consist of sub-steps, as detailed in Table 1.1. The three major steps are to identify the mission risks, determine the appropriate mitigation techniques, and to closely monitor the progress of the risks.[2] By identifying, mitigating, and tracking the risks, it is believed that the mission will have a higher chance of success. There exist many examples of large-scale missions using the risk management process.[3,4,5,6,7,8,9] Many of these missions, however, use high fidelity models, including quantitative assessments like Probabilistic Risk Assessment (PRA). Because of the limited resources and short program life-cycle of small satellite missions, it is desirable to avoid the more expensive and detailed methods of risk analysis such as PRA by employing analytical methods of identifying and tracking mission risks using common low-cost software tools. The following sections describe how cost-conscious missions may apply the risk management methodology from Table 1.1 to the small satellite platform. This risk management plan for small satellites was first published by Brumbaugh in 2012; the published article includes a case study as an example of how to apply the process.[10]

Table 1.1 - Steps of a Risk Management Plan

Main Step	Sub-steps
A. Risk identification	1 Review the mission concept of operations 2. Identify root causes 3. Classify priority of risk 4. Name responsible person 5. Rank likelihood (L) and consequence (C) of root cause 6. Describe rationale for ranking 7. Compute mission risk likelihood and consequence values 8. Plot mission risks on L-C chart
B. Determine mitigation techniques	Choices consist of: 1. Avoid the risk by eliminating root cause and/or consequence 2. Control the cause or consequence 3. Transfer the risk to a different person or project 4. Assume the risk and continue in development
C. Track progress	Plot the mission risk values on an L-C chart at key life-cycle or design milestones to see progress.

1.1.1 Risk Identification

Before analyzing the mission risks, one must first identify the events which could cause harm to the spacecraft and/or mission. The process of risk identification has several steps:

Review mission concept of operations

To determine the risks which could potentially cause mission failure, it is useful to start with the mission concept of operations and the primary payloads. Often times launch and on-orbit checkout are the first steps of the concept of operations. With this approach in mind, what mission-specific actions would cause launch and on-orbit checkout to fail? The spacecraft design and integration team cannot control launch failures, but they can control spacecraft delivery delays. Moving along in the concept of operations to the primary mission phase, consider what could cause the mission payloads to not function properly. Mission risks are higher-level failures; component and system-level failures are the root causes of mission risks which are discussed in the next section. All risks should be analyzed in terms of hardware, software, and programmatic issues.[11] Table 1.2 lists typical sources of mission risk according to the Department of Defense (DoD) Risk Management guide.[2]

Table 1.2 - Sources of Mission Risk

Hardware/Software	**Programmatic**
Requirements	Logistics
Technical baselines	Concurrency
Test and Evaluation	Cost
Modeling and simulation	Management
Technology	Schedule
Production/Facilities	External factors
Industrial capabilities	Budget

Identify root causes for each risk

The next step in assessing the potential risks to a spacecraft mission is to analyze the root causes of such a risk. Starting with the risks identified from the previous section, determine what hardware, software, or programmatic issues would eventually lead to the harmful event occurring. While the mission risks may be very similar between different university and industry missions, the root causes may greatly differ based upon the engineering practices in place in each environment. For instance, student teams may experience different personnel risk root causes than industry spacecraft projects which have career engineers as part of the team. Additionally, university projects tend to have smaller budgets leading to a higher cost risk. With each mission risk, it is encouraged to examine the requirements verification matrix, project schedule, budget and mission overview documents to determine what root causes may contribute to the specified mission risk.

Assign responsible person

While the systems engineer and program manager are ultimately responsible for the risk analysis and management of the entire spacecraft and mission, respectively, the entire team should be held responsible for the mitigation of mission risk root causes. Thus, it is important to identify a responsible person for each root cause. This person should be the most knowledgeable about the root cause and to whom questions regarding its status will be directed. Most likely, the subsystem or task leads are the responsible persons, but this may not always be the case.

Rank likelihood and consequence of root cause

After having first identified the mission risks, their root causes, and named a responsible person for every root cause, each risk must then be ranked according to its likelihood and consequence (L-C). Both of these rankings are typically based upon a 1-5 scale where a value of “1” is viewed as the least severe while “5” is most critical. These scales, however, greatly vary in the descriptions of each value based upon the source. The most detailed set of the two scales found, which is used in this analysis, is from the DoD Guide to Acquisition shown in Table 1.3 and Table 1.4.[2] The decision of the root cause L-C value should be made by consensus of the identified person responsible, systems engineer, and program manager.

While the likelihood criteria of Table 1.3 may be similar across many sources of L-C ranking scales, the DoD has identified three methods of assessing the consequence of a root cause occurring in terms of the technical, schedule, and cost implications to the mission. Table 1.4 quantifies the schedule and cost of each consequence level. Note that the values of the two columns labeled "…application to CubeSats" in Table 1.4 have been added by the author and are specifically tailored for a 3U CubeSat mission with a budget of $1.5 Million (including personnel costs) and timeline of three years from design to launch with design reviews every six months. However, these schedule and cost values can easily be modified to reflect a different scale mission.

Table 1.3 - DoD Likelihood Criteria for Risk Ranking

Level	**Likelihood**	**Probability of occurrence**
1	Not Likely	~10%
2	Low Likelihood	~30%
3	Likely	~50%
4	Highly Likely	~70%
5	Near Certainty	~90%

Table 1.4 - DoD Consequence Criteria for Risk Ranking

Level	Technical	Schedule	Schedule application to CubeSats	Cost	Cost application to CubeSats
1	Minimal or no consequence to technical performance	Minimal or no impact	No change	Minimal or no impact	No change
2	Minor reduction in technical performance or supportability, can be tolerated with little or no impact on program	Able to meet key dates.	Slip < 1 month	Budget increase or unit production cost increases (1% of budget)	Increase < $10K
3	Moderate reduction in technical performance or supportability with limited impact on program objectives	Minor schedule slip. Able to meet key milestones with no schedule float.	Slip < 3 months	Budget increase or unit production cost increases (5% of budget)	Increase < $50K
4	Significant degradation in technical performance or major shortfall in supportability; may jeopardize program success	Program critical path affected.	Slip < 6 months	Budget increase or unit production increase (10% budget)	Increase < $100K
5	Severe degradation in technical performance; cannot meet key technical/supportability threshold; will jeopardize program success	Cannot meet key program milestones.	Slip > 6 months	Exceeds budget threshold (10 % of budget)	Increase > $100K

Describe rationale for the L-C ranking

During the likelihood and consequence ranking of each root cause, it is important to also include a rationale for the choice of the value made. This communicates the current status and issues surrounding each root cause to other team members and program evaluators. Additionally, if the root cause L-C values are tracked over time, the rationales can include updates for increasing or decreasing the L-C values.

Risk Priority Classification

With likelihood and consequence values assigned to each root cause event, the priority that should be given to assigning labor and financial resources to a given root cause can be objectively quantified. One method for assigning risk priorities is provided as follows. First determine the L-C product by multiplying the likelihood and consequence values together for a given root cause. Next, sort the root causes by highest to lowest L-C product, and assign a numerical priority of "1" to the root cause with the highest product. Assign a "2" to the next highest L-C product, and so on. It should be noted that with this method there may be multiple root causes with a given priority level. This product-based method of assigning L-C priorities is one of potentially many methods. The algorithm for assigning priorities can be adjusted if a different method is preferred.

Determine mission risk L-C values

After identifying the mission risks and their associated root causes and deciding upon an L-C value and rank for each root cause, each mission risk L-C value is calculated based on a weighted average of all its root cause L-C values. Many weighting methods exist and the algorithm used here for assigning weights is based on historical practice. The weight associated with each root cause in this analysis is determined by a rank reciprocal method, given by Equation (1.1).[12]

$$w_i = \frac{1/R_i}{\sum_{j=1}^{N} 1/R_j} \tag{1.1}$$

In the above equation R_i corresponds to the ranking of root cause i, and N is the total number of root causes for a given mission risk. When compared to a rank sum or uniform weight methodology, the rank reciprocal method was chosen because it placed larger weight values on the higher ranked root causes. Future analysis is recommended to determine an optimal ranking method. Using this rank reciprocal methodology, each root cause is given a weighting factor between 0 and 1. The total mission risk L-C value is then calculated by multiplying the root cause likelihood or consequence value by its weighting factor and summing over all the root causes. This algorithm for determining L-C values can be modified if an alternate method is preferred.

Plot mission risks on the L-C chart

Each of the mission risks first identified and developed with more detail throughout the previous sections is plotted on a Likelihood-Consequence (L-C) chart to provide a graphical representation of the project risk status. This chart is comprised of a 5x5 grid. The horizontal axis is the consequence axis while the vertical axis displays the likelihood of the risk occurring. The upper right portion of the grid is colored red to signify that risks which are placed in this area should cause serious concern and redistribution of resources. The lower left portion of the plot is commonly colored green to indicate these risks are not currently jeopardizing the potential to successfully complete the project. The region between the red and green areas is colored yellow to show the risks which are being managed but are not an imminent threat to mission success. Mitigation techniques are discussed in the next section.

1.1.2 Determine Mitigation Techniques

After identifying the risks and their root causes, the risk management plan is not complete until a mitigation strategy is determined. According to the DoD, risk mitigation is the selection of the option that best provides the balance between performance and cost.[2] Risk mitigation can be accomplished in four possible ways—avoid, control, transfer, or assume:

1. Avoid risk by eliminating root cause and/or consequence;
2. Control the cause or consequence;
3. Transfer the risk to a different person or project; or
4. Assume the risk and continue in development.

For each of the risks and their identified root causes, at least one mitigation strategy should be adopted. Having multiple methods of mitigation decreases the risk likelihood and consequence upon the mission. As the design status matures, these mitigation strategies also mature. The choice of mitigation technique is dependent upon the project resources available and may also be dependent upon the nature of the program–i.e. whether it is a university, industry, or government project.

1.1.3 Track Progress

To monitor the progress of the mission risks via the mitigation strategies described in the previous section, re-evaluate the L-C values at key life-cycle or design milestones such as design reviews. The program manager and systems engineer should consult with subsystem or task leads as identified in the "responsible person" column of the risk assessment to obtain the most recent status of each root cause when completing the re-evaluation. Ideally, both of the L-C values will decrease with each successive re-evaluation. However, if the mission risk increases in either likelihood or consequence, this re-evaluation will capture the change. For visualizing the change in mission risk L-C values, plot the previous and new mission risk coordinates on an L-C chart with arrows showing the L-C value movement.

1.2 Risk Management and Decision Making in Other Industries

While the focus of this research is in applying risk management and decision making principles to the small satellite platform, it is important to realize that risk and decision analysis are crucial in many industries. Risk analysis and decision-making are closely tied in industries such as insurance, investment and banking, nuclear and chemical, oil and gas, public health and medical, as well as when dealing with natural disasters, system acquisition, and matters of national security.

1.2.1 Insurance

One definition of risk, according to the insurance industry, is a state in which losses are possible. For the purposes of insurance, loss is considered a disappearance or reduction in value, or an unfavorable deviation from expectations.[13] Risk management to the insurance industry consists of comparable steps to those mentioned in Section 1.1: establishing objectives, identifying exposures to loss, evaluating measurable aspects of the exposures, selecting the best method for handling risks, implementing the handling methods, and reviewing the program continuously. Risk handling, according to the insurance industry, involves four options which are similar to the options of Section 1.1.2: avoidance, loss prevention and reduction, retention, and transfer. Also analogous to the aerospace application, prevention involves reducing the probability of a loss occurring while reduction lessens the severity of such a loss.

The fundamental purpose of the insurance industry is to be a vehicle of transferring risk from people or corporations to a separate entity, because the people or corporations do not want to be liable for the risk. Insurance companies are responsible for analyzing claims and determining the policy for which an entity, be it a person or a corporation, is eligible. The process is extremely similar across all the sub-categories of insurance, whether vehicle, home, or life insurance. The insurance industry assesses the risk the entity poses to the company, and classifies the entity into different premium levels based on this assessment. The type of assessment could be based on a class rate or an individual rate. A class rate system will group the entity in with other entities of a similar classification, while an individual rate will base the rate solely on the entity's historical and likely future exposures.[14] The classification methods may vary based on the company and type of insurance. In automobile insurance, for example, classifications may be based on the type of vehicle (commercial vs. private), type of driver (sex, age, health, accident record), and the location (city vs. rural). Many classification methods, though, rely upon regression and statistical analysis to predict the type and number of claims the person may submit to the company.[15,16,17] Additionally, insurance companies rely upon the law of large numbers and pooling principles to ensure that premiums are high enough to cover the insurance company's expenses as well as all claim payments.[14]

1.2.2 Investment, Banking, and Business Development

Many companies employ considerably detailed risk and decision analyses when determining whether or not to invest in other entities, be they companies, countries, or people.[18,19,20] In fact, one article mentions that their company applied decision analysis to capital investment, product and process development, acquisitions, licensing, and business/market strategy.[21] The same article indicates that decision analysis makes it possible to quantify all known critical factors, and has saved time while providing a "rational solution [to] complex problems."

1.2.3 Nuclear, Chemical, Oil, and Gas

The nuclear and chemical industries have been studying risk and decision analysis for a long time, and have been instrumental in developing numerous analytical tools, such as the SAPHIRE tool, for conducting these analyses.[22] Because nuclear and chemical incidents have such low probability of occurring, but have a large consequence, they are considered Low-Probability High-Consequence events. Risk assessments, including the use of PRA techniques, have been applied to many scenarios ranging from developing safety goals to developing models of possible scenarios and probabilities of these scenarios.[23,24,25,26,27]

As with the nuclear and chemical industries, the oil and gas industry deals with low probability but high consequence events. Many studies exist which deal with determining the risk acceptance posture for companies when it comes to certain situations such as oil spills.[28,29,30,31] That is, how much risk is the company willing to accept before implementing risk reduction measures. This type of analysis typically combines both risk assessment as well as decision analysis. Additional examples of decision analysis within the oil and gas industry include decisions companies face on whether or not to build oil rigs or develop a site.

1.2.4 Public health and Medical

Doctors, nurses, and patients are often faced with difficult decisions; for example, whether or not to accept a transplant, amputation, or drug treatment. Whether formalized on paper or not, risk and decision analysis is used to determine the course of action.[32,33,34] Specifically, the people involved determine the possible outcomes for each line of treatment, the likelihoods of these outcomes, and then decide on the path with which they feel most comfortable.

1.2.5 Natural disasters and other industries

Risk and decision analysis can help to more adequately prepare for natural disasters such as floods, earthquakes, and fires. By completing these analyses, risk reduction measures can be established which will reduce the impact of the events when they do occur, since natural disasters cannot be prevented.[35,36,37]

Risk and decision analysis is not just limited to the industries listed above. Risk analysis is also applied in system acquisition, project management, terrorism and national security, market forecasting, artificial intelligence, and computer science.[38,39,40,41,42,43,44]

1.3 SMALL SATELLITES

Satellites have been built and launched for over sixty years. Initially, satellites were small with simple payloads. Over time these payloads became bigger, necessitating larger, more complex and expensive spacecraft. In the past decade, small satellites have reemerged as a lower cost alternative space platform. There are four classifications of small satellites, summarized in Table 1.5, which are gaining in popularity. Those spacecraft having a mass between 0.1-1 kilograms are considered "picosatellites" while those with masses between 1 and 10 kilograms are called "nanosatellites." Larger classes of spacecraft include "microsatellites" and "minisatellites", having masses between 10-100 kg and larger than 100 kg, respectively. This research considers small satellites those spacecraft with a mass less than 100 kg. The University of Texas at Austin is currently developing nanosatellite missions, which will be explained in the next section.

Table 1.5 – Satellite classification by typical mass ranges.[45]

Satellite classification	**Typical Mass Range**
Picosatellites	0.1-1 kg
Nanosatellites	1-10 kg
Microsatellites	10-100 kg
Minisatellites	>100 kg

California Polytechnic State University has established a standard launch mechanism for nanosatellites called the Poly-Picosatellite Orbital Deployer (P-POD). The P-POD is flown as a secondary payload on unmanned launch vehicles, making it easier for small satellites using the system to obtain launches. In order to use the P-POD, the spacecraft must be built in the shape of 10 cm cubes – called CubeSats. One CubeSat volume is called a 1-Unit (1U) and has a mass of approximately 1 kg. Multiple CubeSat volumes may be combined to form various size configurations of Units, such as 1U, 2U, and 3U. The current standard P-POD secondary launcher has a 3U size capacity, although larger launchers are starting to become available. The P-POD and CubeSat standards were first demonstrated together in June 2003 with the launch of two P-POD devices and a total of six 1U CubeSats.[46] Because of their lower cost and ability to rideshare on rockets with other satellites, CubeSats are becoming a popular configuration for small spacecraft missions, particularly by university labs.

1.4 Texas Spacecraft Laboratory

Founded in 2003, the Texas Spacecraft Laboratory (TSL) at the University of Texas at Austin (UT-Austin) has an established research program of designing, building, launching, and operating student-built satellites. The lab has launched two nanosatellites (~25 kg each) and one pico-satellite (~1 kg) within the past 5 years, FASTRAC and Bevo-1, respectively. The RACE mission was delivered and launched aboard the Antares rocket in October 2014, which unfortunately exploded shortly after liftoff. Currently in the TSL, student teams are designing two 3U CubeSats (~4 kg) for launch in 2015 and 2016, Bevo-2 and ARMADILLO. Additionally, students are involved with multiple research projects including interplanetary CubeSat missions, solar sail navigation design, spacecraft software design, small satellite risk management, and optical navigation. Having multiple missions and research projects in development provides a unique perspective to study the design practices, including risk identification and mitigation, for 3U CubeSats across separate platforms. The TSL has learned lessons throughout previous mission life-cycles, such as the usefulness of documentation and quality control standards, to mitigate mission risks. Now, the TSL is applying these lessons and risk identification and mitigation techniques to the development of the current missions in order to improve their chances of mission success.

1.4.1 FASTRAC

Formation Autonomy Spacecraft with Thrust, RelNav, Attitude and Crosslink, also known as FASTRAC, was the winning entry of the University Nanosatellite Program (UNP) UNP-3 competition in January 2005. FASTRAC was comprised of the two satellites shown in Figure 1.1 – named Emma and Sara Lily – with the goals of demonstrating two-way inter-satellite crosslink, performing on-orbit real-time relative navigation using the Global Positioning System (GPS) and demonstrating real-time GPS attitude determination.

As part of the UNP regulations, the design and fabrication of the two FASTRAC satellites were completed entirely by students. Faculty and industry contacts, however, served as advisors and mentors. Additionally, it should be noted that based on Table 1.5, FASTRAC is considered a microsatellite. With a total mass of approximately 25 kilograms each, the two spacecraft do not meet CubeSat specifications.

FASTRAC was launched aboard STP-S26 on 19 November 2010 and was operational for approximately 3 years once it was powered on at 30 minutes after separation. The first beacon was reported five hours after launch. Most of the mission objectives were accomplished, and as of this writing the spacecraft are still in orbit, although they are no longer operational. The two satellites have provided many lessons in documentation methods, ground operations, and satellite design processes which ensured a successful delivery of RACE, and are currently being applied to the Bevo-2 and ARMADILLO satellites. FASTRAC's success serves as a role model for future university satellite design projects.

Figure 1.1 - FASTRAC satellites

1.4.2 LONESTAR – Bevo-1 and Bevo-2

Bevo-1 was the first of four proposed missions in a joint-university NASA-sponsored satellite program called LONESTAR, Low Earth Orbiting Navigation Experiment for Spacecraft Testing Autonomous Rendezvous and docking. The first mission was designated as LONESTAR-1. UT-Austin and Texas A&M University each designed and built two picosatellites which were launched together aboard Space Shuttle STS-127 Endeavour on 15 July 2009, as shown in Figure 1.2. The main mission objectives of the LONESTAR-1 mission were to demonstrate a CubeSat compatible spacecraft bus and to test a Dual Radio Frequency Astrodynamic GPS Orbital Navigator (DRAGON) designed at NASA Johnson Space Center (NASA-JSC). Unfortunately, upon ejecting from the Space Shuttle Payload Launcher, the two satellites failed to separate and thus neither satellite could successfully accomplish its mission objectives. However, both satellites were successfully integrated and demonstrated to work prior to launch.

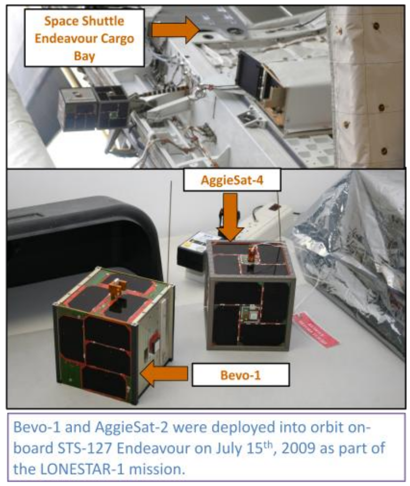

Figure 1.2 - Bevo-1 and AggieSat-2, part of the LONESTAR-1 mission. Above: Deployment of Satellites from STS-127. Below: Close-up view of picosatellites. Photo credit: NASA

Currently, the TSL is finishing software testing on the Bevo-2 3U CubeSat; the integrated flight unit is shown in Figure 1.3. Bevo-2 will complete proximity operations experiments with the Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA) class AggieSat-4 in the second of three LONESTAR missions. Bevo-2 features active attitude determination and control, crosslink communication, a cold gas thruster made from additive manufacturing, and star tracker technology. Bevo-2 will be stowed inside of AggieSat-4, and together, the satellites will be deployed from the ISS JAXA airlock slated for sometime in 2015. This second mission is meant to demonstrate the technology necessary for autonomous rendezvous and docking of two small satellites.

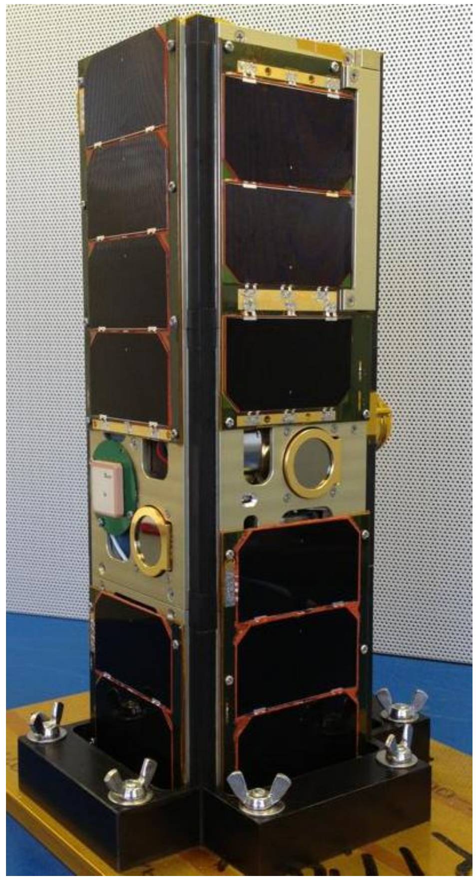

Figure 1.3 - Bevo-2 integrated flight unit. Photo credit: Texas Spacecraft Lab

1.4.3 Texas 2-STEP / ARTEMIS

The Texas 2-STEP mission began as ARTEMIS (Autonomous Rendezvous and rapid Turnaround Experiment Maneuverable Inspection Satellite), which was the UT-Austin entry into the UNP-4 competition in January 2005. ARTEMIS was re-branded as Texas 2-STEP for the UNP-5 competition.

The main objectives of Texas 2-STEP were to rendezvous a chaser and target satellite from a minimum stand-off distance and to demonstrate the maneuvering satellite capabilities necessary for proximity operations as well as the on-orbit demonstration of a camera. Additionally Texas 2-STEP aimed to develop a reusable satellite bus design in order to demonstrate rapid integration of a flight-ready satellite.

Having not been selected as the UNP-4 or UNP-5 competition winner, the Texas 2-STEP project was concluded without launch into orbit. But the lessons learned from the design process have been implemented into TSL projects since then.

1.4.4 RACE

The Radiometer Atmosphere CubeSat Experiment, RACE, was a 3U CubeSat mission studying the 183 GHz water vapor line. RACE was a partnership between the Jet Propulsion Laboratory (JPL) and UT-Austin. JPL provided the radiometer science experiment as well as environmental testing support. UT-Austin was responsible for the design, integration, and functional testing of the spacecraft. The left image of Figure 1.4 shows solar panel testing completed on the RACE flight unit at UT-Austin. RACE was intended to demonstrate low noise radiometer performance and 183 GHz radiometer internal calibration strategies. It would have been the first spacecraft to have a 183 GHz LNA front-end receiver in space, electronically calibrated 183 GHz receiver, and a 183 GHz direct detect system. This mission would have been a major step in the direction of constellation systems, as it provides a technology demonstration of the radiometer on a CubeSat platform.

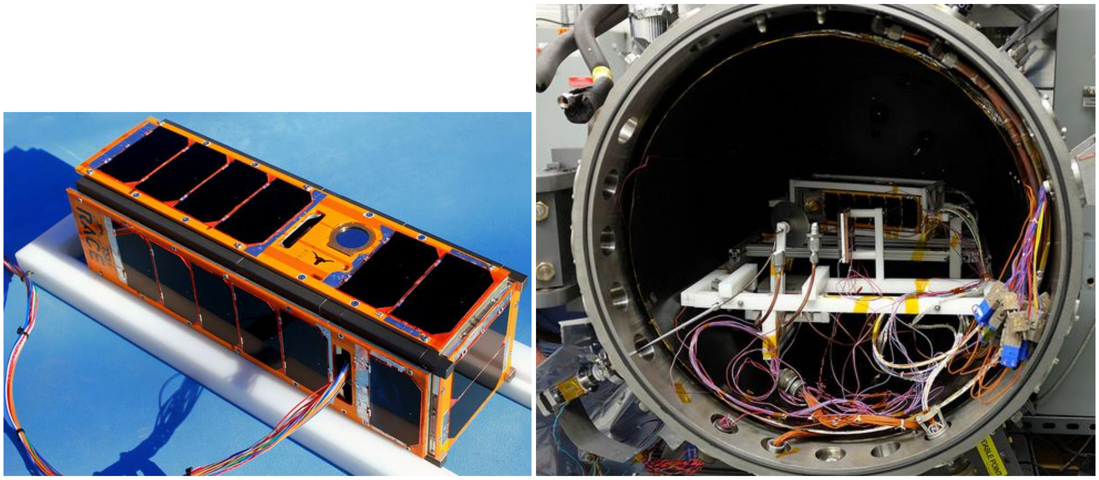

Figure 1.4 - RACE flight unit undergoing solar panel testing (left) and vacuum chamber testing (right). Photo credits: Texas Spacecraft Lab (left) and Jet Propulsion Lab (right)

UT-Austin was given the go-ahead in April 2013 and delivered the flight unit to JPL for environmental testing, shown on the right in Figure 1.4, in February 2014. Unfortunately, as mentioned previously, RACE was aboard the Orbital Sciences Cygnus Crew Resupply mission on the Antares rocket which exploded shortly after liftoff on 28 October 2014.

1.4.5 ARMADILLO

Space debris is an urgent topic of discussion throughout the aerospace industry. Most of the time, discussion focuses on larger debris (>1 cm in diameter) which could cause catastrophic impact damage. However, small particles of sub-millimeter size can cause serious damage as well. Unfortunately, little is known about this small particle size range and its distribution in Low Earth Orbit. As of today, these small particles cannot be tracked from ground radar systems.

In an effort to study this sub-millimeter level particle size range, UT-Austin has developed a 3U CubeSat named ARMADILLO, Atmosphere Related Measurements And Detection of submILLimeter Objects. The sub-millimeter space particle detection instrument is a Piezoelectric Dust Detector (PDD) which is being developed at the Center for Astrophysics, Space Physics and Engineering Research (CASPER) at Baylor University, and can be seen in Figure 1.5 on the end of the spacecraft.

Figure 1.5 - ARMADILLO engineering unit design. Photo credit: Texas Spacecraft Lab

ARMADILLO will study and characterize space debris in Low Earth Orbit (LEO) using the PDD.[47] In order to precisely point the PDD space debris and cosmic dust experiment to obtain the best scientific results, the ARMADILLO picosatellite will have a precise six degree-of-freedom attitude control system. The satellite will also establish optical navigation and provide an independent verification of the GN&C unit with an in-house developed star tracker, as well as have the capability to reprogram the on-board computer while in orbit. ARMADILLO will also study the Total Electron Content (TEC) in the atmosphere through the GPS radio occultation measurements of a dual frequency

GPS receiver, developed by the Radio Navigation Laboratory at UT-Austin.[48] Finally, the CubeSat serves an educational purpose in training students in systems engineering processes.

In January 2013, ARMADILLO won the University Nanosatellite Program in the CubeSat class. Additionally, the 3U CubeSat was awarded a launch opportunity through NASA's ELaNa CubeSat Launch Initiative in spring 2012 and is expected to launch in late 2016.

1.4.6 INSPIRE

The two 3U CubeSats which comprise the Interplanetary NanoSpacecraft Pathfinder In a Relevant Environment, INSPIRE, are a combined effort across four university partners with JPL managing and building the spacecraft. The 3U CubeSat pair will be the first CubeSats to travel beyond LEO. The primary mission objective of INSPIRE is to "Demonstrate and characterize key nano-spacecraft telecommunications, navigation, command & data handling, and relay communications for mother-daughter."[49] The INSPIRE mission statement is to "…enable a new class of interplanetary explorer, while providing components to reduce the size and cost of traditional missions." UT-Austin has delivered a cold gas attitude control system, seen in Figure 1.6, for rotation and translational attitude control. This cold gas design was originally developed for the Bevo-2 mission and has since been adapted for numerous other platforms, including INSPIRE.

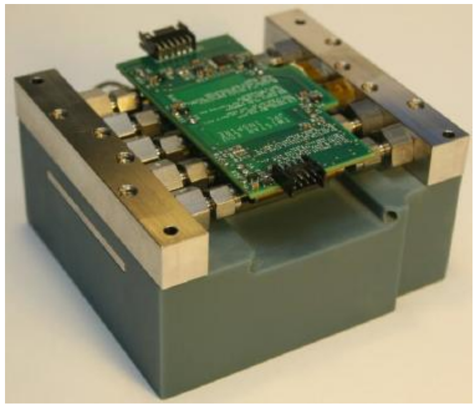

Figure 1.6 - INSPIRE cold gas attitude control system. Photo Credit: Texas Spacecraft Lab

1.4.7 Research Projects

Many students who become involved in the TSL, quickly find research projects that become their undergraduate honors, Master's, or Doctoral theses. Graduate student projects in the lab and research group have included:

- Constrained Attitude Pathfinding as part of the integrated GN&C CubeSat module for three-axis stabilized missions
- Autonomous Rendezvous & Docking algorithms to accomplish the LONESTAR goals
- Command and Data Handling software design for multiple CubeSat missions
- Instrumented six degree-of-freedom thruster, as explained in Section 1.4.6
- Visual and Infrared Proximity Navigation
- Solar Sail mission design as part of the Sunjammer mission
- CubeSat risk management, the topic of this dissertation

1.5 RESEARCH MOTIVATION

The research into small satellite risk management came about because of the author's involvement in the Texas Spacecraft Laboratory (TSL) as the Lead Systems Engineer for many years. Additionally, she was the Student Program Manager for the ARMADILLO 3U CubeSat mission. As part of her duties, she compiled an initial risk assessment of the ARMADILLO mission for inclusion in UNP competition deliverables. While researching risk management plans, she learned that no concrete, step-by-step process existed for small satellites, and the processes that did exist were meant for much larger projects in terms of money, people, and time. The risk management plans found were intended for large missions such as the Space Shuttle or the International Space Station and utilized subjective reasoning in which an analyst's experience level could significantly change the assessed risk level. Specifically, the Likelihood and Consequence values were subjectively chosen on a one to five scale based upon the analyst's opinion of the risk. These existing tools typically required too much time and experience for a university mission, or for satellite designers just entering the industry, to understand and quickly generate results. Therefore, a need was identified to provide a quick and easy-to-use software tool that mission designers of all ages and experience levels could use quickly and effectively.

During her experience researching and writing her Master's thesis on cost and reusability of small satellites, the author learned of many cost models, their general layout and procedures.[50] After having determined to pursue the development of a small satellite risk management plan and associated software tools as her PhD research, the author decided that many of the same methods used in the cost models would be useful for the risk analysis software tools. Namely, the use of user interface forms; summary, plots, and outputs pages; and the use of general error regression to find a relationship between input and output variables.

With the step-by-step and user-friendly concepts in mind, the author talked with many mission designers within the small satellite industry and learned what would be of use to these potential users. It is with all of these suggestions that the risk analysis tools to be described throughout the dissertation were created.

1.6 Contributions to the Field

Reliability and risk analysis is a vital tool in the life-cycle of a spacecraft, and yet no scientific process exists for assessing risk on small satellite missions. While others have completed statistical analyses of spacecraft reliability according to mass categories, previous research classifies a "small spacecraft" in the mass range of 0-500 kg.[51,52] Currently, typical CubeSat missions have an allocated mass of 1-12 kg, depending on the form factor. Risks associated with larger class (500 kg) missions do not necessarily reflect risks associated with these small satellite, or CubeSat, missions. Furthermore, the initial phase of this PhD research is the first to indicate the root causes of mission failures or provide a detailed risk management method which is applicable to small satellite missions, but this portion of the research relies upon the user's subjective opinion of ranking likelihood and consequence values.[10] The CubeSat Risk Analysis tool is the first published method for calculating the risks of CubeSat missions based solely on a handful of Factors of Interest (FOI).[53]

For CubeSat missions, particularly of the university class, more detailed methods of risk analysis such as Failure Modes and Effects Analysis (FMEA) and Probabilistic Risk Assessment (PRA) are unfeasible. While FMEA and PRA are used throughout the aerospace industry, such as for the International Space Station, they typically require large amounts of labor hours in order to complete the analysis pertaining to a given system. While the resulting analysis may be useful for the larger spacecraft and missions, the same level of intensity is not appropriate for most CubeSat missions. For example, many mission designers are interested in CubeSat missions because they are typically cheaper and require less time and people. If the goal is to keep the mission as inexpensive as possible and to get the satellite in orbit as quickly as possible, then a long and detailed analysis process would seem wasteful and counter-productive. Also, many of the risk analysis programs delve into the "what-ifs" and analyze redundancies; CubeSat missions typically do not have hardware redundancy because of the compact form factor. Additionally, these industry tools usually require access to mission database information and software tools, which may be restricted. CubeSat missions typically do not have the required budget, schedule, or personnel resources that are necessary to conduct a full FMEA and PRA analysis.[54] The CubeSat Risk Analysis software tool developed during the course of this research offers a free method of identifying key mission risks that is easily accessible and usable by people of all experience levels. Furthermore, this software tool is scaled to the level useful to CubeSat missions. That is, the tool is not too detailed and yet not too simple.

Similarly, decision analysis tools exist but are not commonly used within the aerospace industry. The existing tools are more commonly used in the investment, oil and gas, and medical fields (see Section 1.2). These decision analysis tools are quite expensive for low-cost or university missions and typically take a lot of time to understand and set up an accurate model. Some software packages include pre-defined decision analysis models which may be useful in some cases, but for the purposes of this research, the pre-defined models limited the analysis capabilities. Moreover, any free version typically has severely limited capability. The software tools developed as part of this PhD research and described throughout this dissertation have been distributed for free access and use. Additionally, the software tools require the user to input their data, but do not require the user to generate the model themselves. The software tools have already stored all necessary calculations and will implement these on the user's command.

The PhD research described throughout this dissertation offers the small satellite community new and innovative software tools to help mission designers better enable full mission success. The goal of the research was not only to create these free and versatile tools, but to enable anyone, regardless of their experience level, to be able to understand and use the tools. As such, there are detailed user's guides which accompany each software tool so as to ensure understanding.

1.7 DISSERTATION ORGANIZATION

This dissertation describes risk management as it applies to small satellites. The first portion of the document describes the CubeSat Risk Analysis software tool, which utilizes the same regression techniques and validation methods as industry cost models to map input demographic parameters to the output risk likelihood and consequence values. The second portion of the dissertation details the CubeSat Decision Advisor software tool including the validation methods used to ensure its proper functionality. The CubeSat Decision Advisor tool uses decision trees and utility theory to guide the user through a series of decisions regarding which mitigation techniques to implement for reducing mission risk.

In this opening chapter, risk management was explored in aerospace applications as well as in the insurance, banking, chemical, oil and gas, medical, and environmental industries. While there are many similarities in how risk is defined and assessed between the industries, the application to small satellites deserves further discussion given the increasing interest in the platform and the current lack of existing risk management tools. This lack of existing tools was explored in more detail in the Motivation and Contributions portions of this chapter, Sections 1.5 and 1.6, respectively.

Chapter 2 defines the mathematical theory used in the development of the software tools. The regression methods are fully explained. The regression models not chosen are also included as reference with the reasons why they were not chosen. Decision trees and utility theory are described with a simple example to show how the two techniques work together and why when combined they are such useful tools for decision analysis applied to small satellite risk management. Multi-attribute utility theory and decision trees are the fundamental techniques used in the CubeSat Decision Advisor software tool.

The regression methods described mathematically in Chapter 2 are then applied to the CubeSat risk analysis problem in Chapter 3 via the CubeSat Risk Analysis software tool. The chapter explains the algorithms for data processing, regression analysis, and designing the software in addition to the method used to gather data from the CubeSat community and the aggregate results of this data collection.

Validating the software is just as, if not more, important as the creation of the software tool itself. Chapter 4 details the methods used to verify that the regression models selected most accurately reflect the data. The methods employed include outlier and trade study analysis, leave-out-one and stratified testing, as well as moving beyond the data range to test the tool's ability to extrapolate.

The second portion of the dissertation begins with Chapter 5 describing the CubeSat Decision Advisor software tool. This tool complements the Risk Analysis tool in that it offers the user a mathematical method, using decision and utility theories, to determine which risks to mitigate and with which mitigation techniques. Chapter 5 explains how the theory of Chapter 2 is applied to this problem, describes the tool, and provides a tutorial example.

Chapter 6 continues the discussion of the CubeSat Decision Advisor by demonstrating its capabilities through validation testing. Unlike with regression analysis, there are no clear-cut methods by which to validate such a tool. For the purposes of this research, the CubeSat Decision Advisor was validated by analyzing mathematically simple and error checking cases in addition to a mission case study, and sensitivity and Monte Carlo analyses.

The dissertation concludes with a summary of the two tools and their impact on small satellite risk management. Future work is outlined for additional student projects or other follow-on work. This dissertation demonstrates that two new easy-to-use tools have been developed for small satellite risk management to be used by mission designers of any project budget and experience level.

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Chapter 2: Mathematical Theory and Background

One goal of this research was to create statistically-based risk management software tools for mission designers of all experience levels to use easily. The CubeSat Risk Analysis tool was the first tool developed, and uses general error regression to obtain the equations which connect the input factors of interest to the output risk likelihood and consequence values. The second tool developed during the course of this research was the CubeSat Decision Advisor tool. While the Risk Analysis tool helps users to identify the risks which are potentially the most mission critical, the Decision Advisor helps these users determine the most effective use of resources to mitigate these risks. The Decision Advisor tool completes its task by using decision, utility, and probability theories. The following chapter describes in detail the mathematical background behind the Risk Analysis and Decision Advisor tools in terms of the regression methods applied, decision trees utilized, utility theory and elicitation methods employed, and general decision making principles.

In order to build a risk analysis model that was based on statistics and data, it was first necessary to gather the data itself. A suitable statistical database of small satellite missions was not available, so one was created. A survey was developed and distributed to the CubeSat community over a seven month period of time. For more details on the survey and the analysis of its results, see Chapter 3. Estimating the mission risk by following statistical methods with historical data gathered from the CubeSat Mission Risk Survey necessitates the creation of a Risk Estimating Relationship (RER) algorithm. Given the traditional approach of defining mission risks in terms of likelihood and consequence values, the RER algorithm defines two separate relationships: Consequence Estimating Relationships (CqERs) and Likelihood Estimating Relationships (LERs).

Based on experience with spacecraft cost models used in industry, it was determined that the RERs should be developed using regression techniques similar to those used in the cost estimating relationship models of packages such as the Aerospace Corporation's Small Satellite Cost Model (SSCM).[1] Basing the RER algorithm on techniques already existing in the community provides a solid starting point for development. But before the details of the algorithm are described in Chapter 3, the rest of this chapter will establish a basic description of regression techniques.

2.1 REGRESSION METHODS

Regression analysis can be a powerful tool when trying to find patterns and describe behavior between input and output variables. These patterns then help to describe current trends and predict future values, which can be useful in many industries. Many times the application of regression in these industries coincides with risk analysis, as described in Chapter 1. There are many formal definitions and types of regression. This section will explain the basic terminology for regression analysis as well as provide typical methods used in classic regression analysis. The section will also describe the limitations of the classical approach while the next section will explain the specific type of regression used during the course of this research.

Kutner et al. describe regression as "…a statistical methodology that utilizes the relation between two or more quantitative variables so that a response or outcome variable can be predicted from the other, or others."[2] They go on to define two types of relationships – functional and statistical. An example of a functional relationship is given in Figure 2.1 (a) while a statistical example is shown in Figure 2.1 (b). Specifically, a functional relation between variables can be expressed in terms of a mathematical formula. That is, all the data fall on a single curve. Conversely, a statistical relation involves data points which do not precisely fall on a curve. Statistical relations are used during the course of this research, since the data gathered during the course of the CubeSat Risk Survey, to be described in Chapter 3, did not perfectly fall on a single curve.

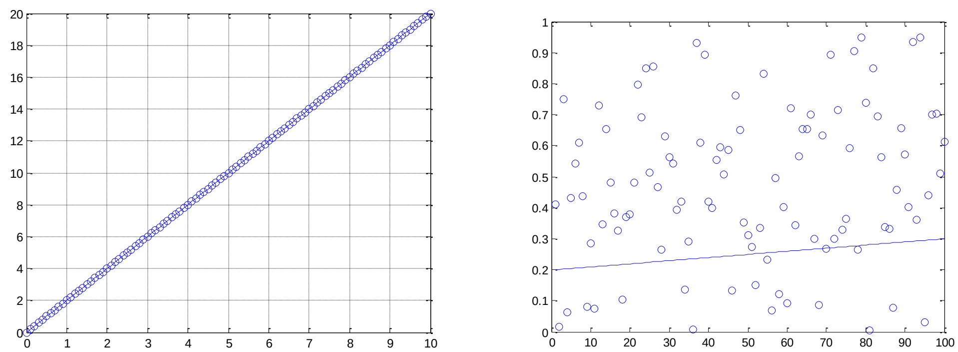


Figure 2.1 – Regression examples: (left) Functional relation; (right) Statistical relation

If the data follows a functional relationship, then there is no need for regression analysis, since the data already perfectly fits a single function. However, if the data follows a statistical relation, then there are many possibilities for a curve fit. The regression methods to be described in the following sections offer techniques to distinguish the function forms and parameters which best represent the data. In many research applications, one regression technique is applied to several function models, and the models themselves are then compared to see which function form best represents the data. Therefore, it is necessary to compare different linear and nonlinear models through various key parameters such as the sum of squared deviations (SSD), standard error of the estimate (SEE), bias, and R^2 values. Each of these quantities will be described quantitatively and qualitatively in the following sections.

The Method of Least Squares, also called Ordinary Least Squares (OLS), is one technique used to determine the parameters of a best fit curve after having first identified the predictor variables and function form. Because of the statistical relationship between the input and output variables, there will exist error between the predicted and actual values. OLS assumes that the function of best fit is of the form shown in Equation (2.1), where Y_i is the observed response in the i-th trial; X_i is the input value or predictor variable; β_0 and β_1 are the parameters to be found through analysis. Notice that the function is linear in the parameters β_0 and β_1. In addition, the model is considered an "additive error" model, because the error term is added to the parameter terms, as opposed to being multiplied. The OLS methodology calls for minimizing the sum squares residual, the sum of the squared difference between the observed value Y_i, the left side of Equation (2.1), and the estimated value given by the right-side of (2.1) without the error term. Because of the error term, these values will not always be equal. The optimization constraint is given by Equation (2.2). The parameters β_0 and β_1 which minimize Q are the parameters for the line of best fit.[3]

$$Y_i = \beta_0 + \beta_1 X_i + \varepsilon_i \tag{2.1}$$

$$Q = \sum_{i=1}^{n} [Y_i - (\beta_0 + \beta_1 X_i)]^2 \tag{2.2}$$

Traditional OLS analysis determines the effectiveness of the chosen predictor variables through statistical tests such as t- and F-tests as well as Analysis of Variation

(ANOVA) tables. If a parameter is identified as being ineffective, it may be removed from the function in favor of a simpler form. In this analysis, the error term is assumed to be normally distributed in addition to being additive. Because of this, the expected value of the error of each observation is unbiased: $E\{Y\} = \beta_0 + \beta_1 X$. Furthermore, the error terms are assumed to be uncorrelated and independent. That is, the outcome of any one trial has no effect on the outcome of a different trial. All these assumptions combine to assume that the Y_i terms are independent and normally distributed. These assumptions are justified for many analyses, because many statistical procedures are only sensitive to large departures from normality. The benefit to these assumptions is the ability to use the aforementioned typical statistical tests such as ANOVA and t- and F-tests for determining the significance of function parameters.[2,3]

However, a linear and additive model severely limits the regression analysis. Linear relationships between the parameters may not always be the best descriptor of trends in data. The same problems persist when OLS is involved in multiple regressions such as the function form shown in Equation (2.3), the polynomial function form in Equation (2.4), or the power form in Equation (2.5). After all, the multiple and polynomial function forms are just extended versions of the basic linear function form in Equation (2.1). When using OLS, power and exponential function forms such as Equation (2.5) must be re-formatted into a linear relationship. Notice that initially the function uses multiplicative error, an OLS assumption when nonlinear function forms are chosen. When the transformation from non-linear to linear is made, a biased solution is created because of the “transformation of the additive error term from logarithmic space to linear space.”[3] Generally, more complex function forms than Equation (2.5) cannot be used with OLS, because it is impossible to transform into the classic linear regression form. Finally, when using an additive error model, “…the additive-error model attempts to minimize the sum of squared deviations from all data points, thus giving the larger data points a perhaps unduly large influence in determining the 'best-fitting' curve."[4]

$$Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \ldots + \beta_{p-1} X_{i,p-1} + \varepsilon_i + \beta_1 X_i + \varepsilon_i \quad (2.3)$$

$$Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 {X_{i2}}^2 + \varepsilon_i \quad (2.4)$$

$$Y_i = \beta X^\alpha \varepsilon_i \quad (2.5)$$

The benefit to using OLS analysis is the known statistical significance tests. But when the function form has been transformed, the parameters are also transformed and must be correctly interpreted in the analysis. All the difficulty with OLS lies in the assumptions regarding the nature of both the parameters and the error terms. The error terms, and thus the response values, are assumed to have a constant variance and are assumed to be additive for linear function forms while multiplicative for non-linear forms. Additionally, error terms are assumed to be uncorrelated, leading to uncorrelated response variables. These assumptions may not be valid for many data sets or analysis purposes. As such, a more generalized regression approach is needed.

2.2 General Error Regression

The SSCM as well as other cost models like the Unmanned Spacecraft Cost Model (USCM) use a technique called General Error Regression (GER).[5,6] The GER method is useful because it allows for both multiplicative and additive error models in more complex relationships such as factor, power, and triad function forms, as opposed to being limited to additive and linear models when using traditional regression methods such as Ordinary Least Squares (OLS). The GER method offers many forms of minimization: Minimum Percentage Error (MPE), Iterated Least Squares / Minimum Unbiased Percentage Error (IRLS/MUPE), and Minimum Percentage Error – Zero Percentage Bias (ZPB-MPE).[7] The preferred method for implementing GER is to use the ZPB-MPE method, which eliminates bias by slightly increasing the minimized value.[8]

2.2.1 Types of General Error Regression

While the Ordinary Least Squares may be useful for initial analysis, more involved regression techniques are necessary for detailed research. General Error Regression (GER) allows the user to choose any function form and any error model, independent of one another. In other words, an additive error model could be paired with a power function form and a multiplicative error model could be included in a linear function form. A key benefit of GER is its easy implementation using computer search algorithms such as Excel Solver, rather than needing to solve sets of simultaneous equations as with OLS. The following sections describe the different methods of GER.

MPE

The Minimum Percentage Error (MPE) method is the GER technique most similar to traditional OLS in that the goal is to minimize the Sum of Squared Deviations (SSD). However, when using a multiplicative error, the SSD now represents the sum of squares of the percentage error. The benefit of using a percentage error involves having "stability of meaning across wide range of programs, time periods, and estimating situations."[9] Meaning, error should be proportional to the magnitude of the parameters.

An error of \$10 expresses different error levels when the total budget is \$100 versus \$100,000. However, a percentage error of 10%, will indicate the same error value no matter the budget. In this way, percentage error allows for the direct comparison between linear and nonlinear models. Since the goal of regression analysis is to choose a function form which best represents the data, being able to directly compare linear and non-linear models is extremely helpful.

The SSD key parameter along with the Standard Error of the Estimate (SEE) and Bias are calculated with the equations given in Table 2.1 when implementing General Error Regression. The calculated value for data point i is given by y_i with $f(\overrightarrow{x_i}, \vec{a})$ representing the chosen function form with the input parameters for a given data point, $\overrightarrow{x_i}$, and the function coefficients vector, $\vec{a}$. At the end of the regression routine, $\vec{a}$ represents the vector of coefficients which minimize the SSD. The error ε_i corresponds to the data point i. The number of data points is n and the number of coefficients for the function $f(\overrightarrow{x_i}, \vec{a})$ is m. Note Table 2.1 provides equations for both additive and multiplicative models. The equations are highly similar; the only differences between the two models being the calculations as a form of percentage in the multiplicative cases.

Table 2.1 - Key parameters for additive and multiplicative error models.[7]

	Additive	Multiplicative
Function form	$y_i = f(\overrightarrow{x_i}, \vec{a}) + \varepsilon_i$	$y_i = f(\overrightarrow{x_i}, \vec{a})\, \varepsilon_i$
Sum of Squared Deviations (SSD)	$SSD_A{}^2 = \sum_{i=1}^{n} \left(y_i - f(\overrightarrow{x_i}, \vec{a})\right)^2$	$SSD_M{}^2 = \sum_{i=1}^{n} \left(\frac{\left(y_i - f(\overrightarrow{x_i}, \vec{a})\right)}{f(\overrightarrow{x_i}, \vec{a})}\right)^2$
Standard Error of Estimate (SEE)	$SEE_A = \sqrt{\frac{1}{n-m}\sum_{i=1}^{n} \left(y_i - f(\overrightarrow{x_i}, \vec{a})\right)^2}$	$SEE_M = \sqrt{\frac{1}{n-m}\sum_{i=1}^{n} \left(\frac{\left(y_i - f(\overrightarrow{x_i}, \vec{a})\right)}{f(\overrightarrow{x_i}, \vec{a})}\right)^2}$
Bias	$B_A = \frac{1}{n}\sum_{i=1}^{n} \left(f(\overrightarrow{x_i}, \vec{a}) - y_i\right)$	$B_M = \frac{1}{n}\sum_{i=1}^{n} \left(\frac{f(\overrightarrow{x_i}, \vec{a}) - y_i}{f(\overrightarrow{x_i}, \vec{a})}\right)$

When implementing the MPE technique, the percentage error is minimized, but a bias is introduced. Book and Lao describe bias as the tendency "…to overestimate the actual values of the dependent variable."[7] Obviously, bias is not desirable in a final function form solution. As such, Tecolote Research Inc. developed the technique called Iteratively Reweighted Least Squares (IRLS), also known as Minimum Unbiased Percentage Error (MUPE), as a potential solution to the issue of bias. The next section describes this technique in more detail.

IRLS/MUPE

Iteratively Reweighted Least Squares (IRLS) was created during the development of the Unmanned Spacecraft Cost Model (USCM) in response to the introduction of bias through the MPE method of GER. In the USCM documentation, IRLS is referred to as Minimum Unbiased Percentage Error (MUPE).[6] This technique necessitates iteration and convergence to a set of function parameters which result in zero bias, but a slightly higher percentage error than the MPE technique.

The IRLS method uses a similar minimization criterion, shown in Equation (2.6) as the multiplicative SSD in Table 2.1. For this technique, though, the optimization is completed multiple times by using the previous set of parameter values as the *a priori* values for the next optimization run. The denominator parameter value vector, $\vec{a}_j$, in Equation (2.6) comprise the *a priori* values. The numerator parameter value vector, $\vec{a}_{j+1}$, is the value optimized in each iteration of the IRLS/MPE method. Because of the iterative nature of this technique, IRLS is difficult to implement.

Despite reducing the bias to zero, Book and Lao show that the IRLS technique is actually minimizing "a weighted sum of additive squared errors."[7] For analysis purposes that call upon multiplicative error function forms, IRLS is not the appropriate GER technique. Because of this limitation, the Zero Percentage Bias, Minimum Percentage Error (ZPB-MPE or ZMPE) technique was created, and is described in the next section.

$$f(\vec{x_i}, \vec{a}_{j+1}) = Min \sum_{i=1}^{n} \left(\frac{\left(y_i - f(\vec{x_i}, \vec{a}_{j+1}) \right)}{f(\vec{x_i}, \vec{a}_j)} \right)^2 \qquad (2.6)$$

ZMPE/ZPB-MPE

The technique preferred by the Cost Estimating Relationship community is the Minimum Percent Error, Zero Bias (ZMPE) method better known as Minimum Percentage Error – Zero Percentage Bias (ZPB-MPE). There are several reasons analysts prefer ZPB-MPE, but at the forefront is its simplicity to implement in Excel using the Solver add-in and its unbiased solution. Additionally, ZPB-MPE allows the user to minimize using an additive or multiplicative model and select any functional relationship to analyze. However, as with all models, ZPB-MPE also has limitations. There is no significance test, such as the t-test, for determining parameter importance. But as mentioned previously, in the development of estimating relationships, these significance tests are not of extreme importance. The biggest drawback of ZPB-MPE method is that the solution may not be a global minimum.[3]

The ZPB-MPE method finds the function form parameter values which minimize the SSD value while holding the bias as close to zero as possible using the equations given in Table 2.1. The technique is easy to implement for either additive or multiplicative error models using Excel Solver or any other optimization program. Additionally, because there is no bias, the resulting calculated values more accurately reflect the actual values. Because of the additional constraint in ZPB-MPE, the percentage error will be larger than with the MPE method. However, recall that MPE had introduced bias whereas ZPB-MPE maintains a nearly zero bias value.[7]

2.2.2 General Error Regression Applied to Risk Analysis

For the development of the CubeSat Risk Analysis Tool, the ZPB-MPE technique was implemented using an Excel Solver routine. The output values, y_i, are the risk likelihood and consequence values. The function forms, $f(\vec{x_i}, \vec{a})$, and input values chosen for the Risk Estimating Relationship (RER) analysis are described in Chapter 3. For each of these functions, the Sum of Squared Deviations (SSD) value was minimized using multiplicative error models while keeping bias (B) equal to zero by changing the coefficients of the functions of interest. The formulas for these values are given in Table 2.1 for both additive and multiplicative models. Recall that the error ε_i corresponds to the data point i, the number of data points is n, and the number of coefficients for the function $f(\vec{x_i}, \vec{a})$ is m.

While the goal of GER and ZPB-MPE is to return a model with the least SSD and zero bias, the function must still be representative of the data. In linear regression the coefficient of linear determination is the square of the Pearson product-moment correlation coefficient, R^2, as given in Equation (2.7).[4] Here, n represents the number of data points, x_i is the dependent variable, and y_i is the observed value. This traditional R^2 value is used to compare across many linear models and select the line of best fit in ordinary least squares methodology.

$$R^2 = \frac{\{n \sum x_i y_i - (\sum x_i)(\sum y_i)\}^2}{\{n \sum x_i{}^2 - (\sum x_i)^2\}\{n \sum y_i{}^2 - (\sum y_i)^2\}} \tag{2.7}$$

The traditional definition of R^2 indicates both the amount of variation that may be explained by linear regression as well as the variation due to other parameters. In linear relationships, though, this variation due to other parameters is subtracted to yield only the variation due to the regression relationship. But in nonlinear forms, there are cross-terms that prevent the subtraction of the other factors. Therefore, the typical calculation of the R^2 value does not mean anything when dealing with nonlinear function relationships.[4,9] Another expression shown in Equation (2.8), called the Generalized Coefficient of Determination, can solve this issue and be used for both linear and nonlinear functions.[9,10] The dependent variable is now the predicted values obtained from the function $f(\vec{x_i}, \vec{a})$, so the generalized R^2 value now gives a fit determination between the calculated estimate values and the actual values instead of a linear fit relationship. This generalized form of the R^2 function is used for comparing linear and nonlinear risk estimating relationship function forms in this analysis.

$$R^2 = \frac{\{n \sum f(\overrightarrow{x_i}, \vec{a}) y_i - (\sum f(\overrightarrow{x_i}, \vec{a}))(\sum y_i)\}^2}{\{n \sum f(\overrightarrow{x_i}, \vec{a})^2 - (\sum f(\overrightarrow{x_i}, \vec{a}))^2\}\{n \sum y_i{}^2 - (\sum y_i)^2\}} \tag{2.8}$$

In many statistical regression analyses, significance tests such as the t- and F-tests are used to determine whether a parameter is useful as an input to the function. Unfortunately, many of these statistical tests require a list of assumptions that could not be guaranteed in this research, such as normality and independence of the error terms. Additionally, for this analysis, the descriptors of interest are the SSD, SEE, Bias, and generalized R^2 values, since these values indicate how well the function will predict future cases. According to Book and Young, in regard to the derivation of the cost estimating relationships (CERs) developed for the Unmanned Spacecraft cost Model (USCM), the "use of t scores looks backward toward statistical derivation of linear CERs with Gaussian residuals, rather than forward toward application of CERs in the cost-estimating process."[9]

Chapter 3 goes into more detail regarding the specific application of these principles to the task of developing Risk Estimating Relationships. Chapter 3 also describes the factors of interest and function forms chosen for analysis, and how the functions were analyzed to select a single model for each root cause Consequence Estimating Relationship (CqER) and the Likelihood Estimating Relationship (LER).

2.3 Decision Analysis

Before explaining how decisions are made, a decision must be defined. According to Howard, a decision occurs when one makes a commitment "to follow a course of action [and] to make an irreversible allocation of resources…”[11] During the course of this research, resources are defined to be in the form of dedicating money, people, or time to mitigate a given mission risk. And so, to make a decision in the context of this research would be to select a certain number of people to work on a given task for a particular amount of time under a budget of a distinct amount. Decision analysis is the study of how these decisions are made, and how to make them in the most effective and logical manner possible. Howard goes on to describe decision analysis as a “combination of philosophy, methodology, practice and application in the formal introduction of logic and preferences to the decisions of the world.”

Decision analysis techniques introduce logic and structure to reduce complex problems to a series of elemental steps, most commonly, by using decision trees. Decision trees represent, “…the structure of all possible sequences of decisions and outcomes…” while also containing information regarding the cost, value, and probability of these outcomes. Often times it is the decision-maker’s preference system being captured by the value placed on various outcomes. Additionally, the probabilities could be based on fact, or they may be elicited from experts. Decision analysis is therefore a normative technique with a goal of “…trying to show how a person subscribing to certain logical rules would make…decisions in order to maximize attainment of his objectives.”[12]

The benefit of using decision analysis techniques, such as decision trees, is that once applied, the results will represent a normative and logical approach, and are thus defendable, but are also representative of a certain value system. In other words, the decision is reduced to choosing the alternative with the highest preference value based on the desires of the decision-maker. Howard and Matheson explain the point of decision analysis is so that "…the impact of uncertainty upon the decision can be measured and interpreted – not left to intuition."[12]

2.3.1 History

Decision analysis has roots, and continues to take part, in military applications. According to Howard and Matheson, the first scientific application of decision-making was used to study air defenses during the Battle of Britain and continued in the study of the protection of the U.S. Navy fleet from submarines. After the end of World War II, portions of operations research became what is now known as management science. Operations research and management science were born from the formal field of decision analysis.[12]

Decision analysis was formalized in part because of technological advancements in the development of the computer. World War II helped to introduce the concepts, but the technological advancements brought decision analysis to the forefront of management science and operations research. Additionally, the transition of companies to boards and committees required that decisions have a well reasoned and documented rationale, something which decision analysis is uniquely poised to offer.[12]

Decision analysis is now a critical component of many industries, as indicated in Chapter 1. Moreover, decision analysis has been used to develop decision support systems such as those in the medical industry and has played a major role in artificial intelligence systems through machine learning.[13] For example, Quinlan mentions three classifications of tasks for which decision analysis is useful:

1. The diagnosis of a medical condition from a list of symptoms,
2. Playing the game of chess, and

3. Weather forecasting based on atmospheric observations.[14]

Decision analysis plays a role in any task involving a robot making decisions based on the knowledge it has stored.

2.3.2 Nomenclature

In order to understand the decision analysis application to satellites, the following definitions and theory should be established:

A decision-maker is "…an individual [group of people or single person] who has the power to commit the resources of the organization."[12]

Since a decision is "an irrevocable allocation of resources," to change a decision would require modifying the amount of the given resource necessary for the decision's implementation.

Probability is a belief that an event will occur, and may differ from person to person. Howard and Matheson define probabilities as a "…measure [of] a person's state of knowledge about phenomena rather than the phenomena themselves."

Decision trees in this research use decision and chance nodes. An example decision tree is shown in Figure 2.2 where there are two alternatives, A and B, each with two possible outcomes, S1 and S2. A decision node is given by a square, and represents a choice to be made between several alternatives. The chance node is shown by a circle, and characterizes the possible outcomes of the alternative, typically noted by probabilities. Chance nodes are evaluated by taking the expectation of that node, whereas decision nodes are evaluated by the maximum value of the alternatives within the decision node. These evaluation methods will be explained in more detail as it applies to this research in Section 2.4 about Utility Theory. Note that decision trees may have any number of outcomes and associated probabilities; Figure 2.2 simply represents a basic scenario in order to explain terminology. For alternative A, the probability of outcome S1 is p, and therefore the probability of S2 is $(1-p)$. Similarly, the probabilities for S1 and S2 in alternative B are q and $(1-q)$, respectively. It is necessary that the probabilities for outcomes of a single alternative sum to unity. The probabilities for the different outcomes may be different between the alternative branches, thus the probability is expressed as depending on the alternative choice; $p(S1|A)$ is read as the probability of outcome S1 given alternative A was chosen.

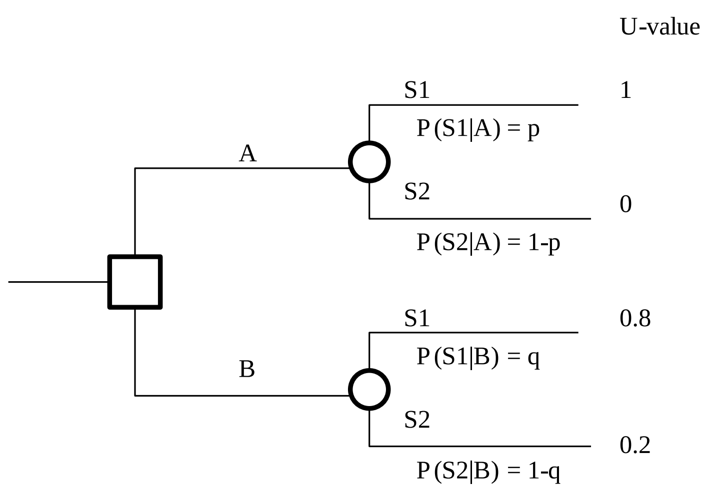


Figure 2.2 - Example decision tree

Decision trees, such as the example in Figure 2.2, are sometimes referred to as "lotteries." Officially, Howard and Matheson define a lottery as "…a set of prizes or prospects with probabilities attached."[12]

The certain equivalent is an expression of the "…amount of worth received for certain so that the decision-maker would be indifferent between receiving this worth and participating in the lottery."[12]

Risk preference typically consists of three types of people: risk-averse, risk-preferring, and risk-indifferent. Risk-averse people tend to be "…willing to forego some expected value in order to be protected from the possibilities of poor outcomes." Risk-preferring people are the opposite, and are "…willing to engage in…gambles that are unfair." Risk-indifferent people are only willing to engage in a fair gamble or lottery.[12]

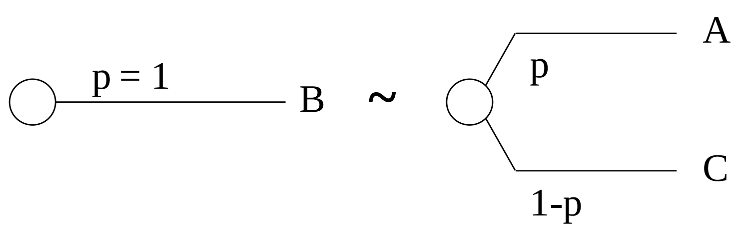
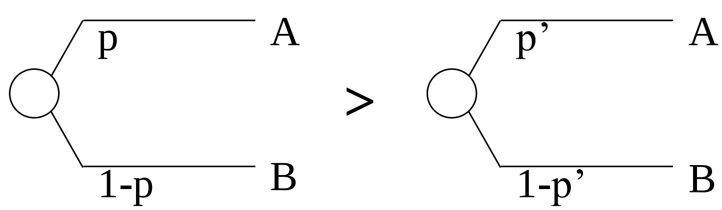
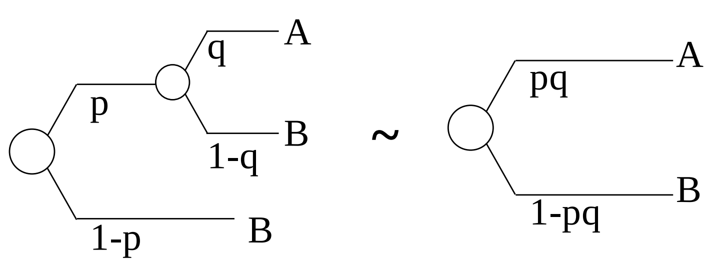
2.4 UTILITY THEORY

In some cases, such as with money or time, it is easy to measure the preference of an outcome. However, not all variables can be ranked so easily; a more general approach is to use utility theory. Utility is defined as a true measure of value to the decision-maker.[15] Furthermore, by using utility as a common measurement, comparisons between alternatives can be made and a set of axioms may be established. Before outlining the rules of utility theory, Table 2.2 explains the language of denoting preference between two alternatives. With the foundation of language as defined in Table 2.2, the axioms of utility theory are described in Table 2.3.[16]

Table 2.2 - Symbolic representation of alternative preferences

Symbols	Meaning
$A \succ B$	A is preferred to B
$A \succcurlyeq B$	A is preferred at least as much as B
$A \sim B$	Indifference between A and B

Table 2.3 - Axioms of utility theory[16]

Property	**Explanation**
(1) Orderability	The preference between alternatives can be arranged in order of increasing preference: $A \succ B,\ A \succcurlyeq B,\ A \sim B,\ A \preccurlyeq B,\ A \prec B$
(2) Transitivity	If $A \succ B$ and $B \succ C$, then $A \succ C$.
(3) Continuity	If $A \succ B \succ C$, there exists a value of p (between 0 and 1) such that a person is indifferent between (a) obtaining B definitely, and (b) getting A or C with probabilities p and $(1-p)$, respectively. This indifference is shown graphically by the following lottery:  If p is 0, getting C is certain, hence, B is clearly preferred. Whereas if p is 1, the lottery implies getting A for sure, and B is not preferred. Therefore, for some value of $0<p<1$, the condition of indifference between (a) and (b) will emerge. In mathematical terminology, B is the *certainty equivalent* of the lottery.
(4) Substitutability	A lottery and its certainty equivalent are interchangeable without affecting preference, and are equally preferred.
(5) Monotonicity	If $A \succ B$, then  If and only if $p > p'$.
(6) Decomposability	A series of branches may be replaced by a single branch, as shown in the following lottery: 

2.4.1 Single Attribute

Assuming that the axioms of Table 2.3 are met, a utility function may be created to map the degree of preference to a numerical format.[16] Utility functions must follow the same axioms as described in Table 2.3. For example, if event A is preferred over event B, than the utility of A must be greater than the utility of B, or $u(A) > u(B)$. Because the preferences are now expressed in a numerical format, the preference of a certain scenario, or lottery, can be calculated. For the purposes of this research, the utility of a lottery is determined by the method of expected utility. It is acknowledged that several other forms of utility calculations exist.[16,17] However, for the development of an initial software tool, expected utility was deemed to be the simplest to implement. Future iterations of the tool could implement these additional methods of utility assessment.

To determine the expected utility of an alternative, $E[u(\cdot)]$, the probability for each outcome of an alternative is multiplied by the utility value (u-value) for that outcome and summed over all the outcomes: $E[u(\cdot)] = \sum p_i u_i$. In the example provided in Figure 2.2, the expected utility for alternative A would be $E[u(A)] = p * 1 + (1 - p) * 0 = p$. Similarly, for alternative B, $E[u(B)] = q * 0.8 + (1 - q) * 0.2 = 0.2 + 0.6q$. The decision-maker would be indifferent between these two alternatives when their expected utilities are equivalent: $E[u(A)] = E[u(B)]$. Otherwise, the decision-maker would choose the alternative with the greater expected utility.[12] Similarly, the continuity axiom of Table 2.3 provides another example. Since the probability of event B is 1, then it's expected utility is simply $u(B)$. The expected utility of the right-side lottery is: $E[u(\cdot)] = p * u(A) + (1 - p) * u(C)$. The axiom states that there must exist a probability p to make these two expected utility values equal, and the decision-maker indifferent between the two options. In other words, $u(B) = p * u(A) + (1 - p) * u(C)$. So, if the utility of events A and C are known, the utility of event B can be determined by establishing an appropriate probability p.[16] This use of the continuity axiom to determine the utility of an event is the basis for utility elicitation and the backbone of the CubeSat Decision Advisor software tool.

2.4.2 Multi-attribute Utility Theory

In many cases it is necessary to determine a joint utility function which combines a set of important variables. Under the assumption of utility and preferential independence, a joint utility function, $u(x_1, x_2, \dots, x_n)$, can be obtained from the combination of the attribute utility functions, $u_i(x_i)$, by finding the k value which satisfies Equation (2.9) given a user's preference system captured by the k_i values.[18] To obtain these k_i values, the decision-maker would be asked whether they prefer attribute x_1 at its best value while x_2 and x_3 are at their worst or whether they prefer attribute x_2 at its best value while x_1 and x_3 are at their worst. A series of such questions fully characterize the k_i values which then allows combination of the attribute utility functions into a joint multi-attribute utility function in accordance with Equation (2.10). The k and k_i values act as weights for the input parameters, placing a user-determined emphasis on the parameters when combining the attribute utility curves into the joint curve.

$$1 + k = (1 + kk_1)(1 + kk_2)(1 + kk_3) \tag{2.9}$$

$$ku(x_1, x_2, \dots, x_n) + 1 = \prod_{i=1}^{n}[kk_i u_i(x_i) + 1] \tag{2.10}$$

For the purposes of this research, the joint utility function $u(x_1, x_2, \dots, x_n)$ determines the user's utility value for the combination of cost, people, and time required for implementing a given mitigation technique. The expected utility value for the mitigation technique is therefore a function of this joint utility value as well as the probability of success for the technique outcome. The optimal mitigation technique choice is the technique which has the maximum expected utility value, as this technique will provide the most value for the given set of input parameters. It is the identification of this optimal mitigation technique that is the primary purpose of the CubeSat Decision Advisor software tool.

2.4.3 Decision Making Principles

By mapping a decision-maker's preference system to the decisions at hand, the decision-maker can more appropriately see which outcomes will benefit their situation. However, in order to do this, the decision-maker must follow the rules of actional thought, as described by Howard[19] and which closely follow the axioms of Table 2.3. The rules of actional thought are: the Probability Rule, the Order Rule, the Equivalence Rule, the Substitution Rule, and the Choice Rule. The Probability Rule indicates that the decision-maker must be able to define probabilities of the possible outcomes to the decision alternatives. The Order Rule aligns with Utility Theory Axioms 1 and 2 in that the decision-maker must be able to arrange all the possible outcomes in order of most to least preferable with consistency (transitivity) upheld. The Equivalence Rule echoes the Continuity Axiom and requires the decision-maker to be able to identify a probability p which would make them indifferent between a experiencing event B and an experiencing event A with probability p or event B with probability $1 - p$. The Substitution Rule says that the decision-maker must be indifferent between scenarios they have already defined as equivalent, and reiterates Utility Theory Axiom 4. The Substitution Rule is helpful in replacing decision tree branches as is shown in the Decomposability axiom. The Choice

Rule requires the decision-maker, when given a choice between two outcomes, to always choose the outcome which they had ranked higher on their preference list. This is equivalent to saying the decision-maker must choose the alternative with the higher expected utility value.

The CubeSat Decision Advisor makes use of the Equivalence Rule when determining the utility curve parameters which describe the user's preference system, as will be described in the next section. The Choice Rule is used in the analysis portions of the tool; the software determines which mitigation techniques provide the maximum expected utility and stores these choices and their associated values at the next highest level of the decision tree as well as on the Summary page. All of these research-specific applications of decision analysis are described in more detail in Chapter 5.

2.5 UTILITY ELICITATION

The utility function can take many forms. During initial tool development, exponential, natural log, linear, and power equation forms were considered. These functions are given in Table 2.4. After talking with experts regarding methods used in the decision analysis industry, it was determined to use the exponential function only, as it provided the most possibilities by simply changing the exponent parameter. The baseline exponential function is given in Equation (2.11). The initial version of the tool found that $a = 0$ and $b = 1$ best represented logical utility preferences with four possible γ values for each of the attributes: cost, people, and time. These parameters are listed in Table 2.5 and are shown graphically for the cost attribute in Figure 2.3 for the people attribute in Figure 2.4, and for the time attribute in Figure 2.5. Note that the attribute utility functions are scaled between the minimum value, 0, and maximum value designated by the user.

Engineering judgment and experience led to the selection of the three sets of four utility functions, and it is acknowledged that an infinite number of alternative functions exist. However, for the purposes of this research, the functions needed to be narrowed down to a select few with which to establish the software program.

$$u(x) = a + be^{-\gamma x} \tag{2.11}$$

Table 2.4 - Utility function equation forms

Function Form	**Equation**
Exponential	$u(x) = a + be^{-\gamma x}$
Natural Log	$u(x) = a * \ln(x + \beta) + b$
Linear	$u(x) = a + bx$
Power	$u(x) = a * x^{\gamma} + b$

Table 2.5 - Exponential parameters for attribute utility functions

	Cost	**People**	**Time**
$\boldsymbol{\gamma_1}$	0.0001	0.05	0.01
$\boldsymbol{\gamma_2}$	0.0005	0.15	0.025
$\boldsymbol{\gamma_3}$	0.001	0.25	0.05
$\boldsymbol{\gamma_4}$	0.002	0.5	0.1

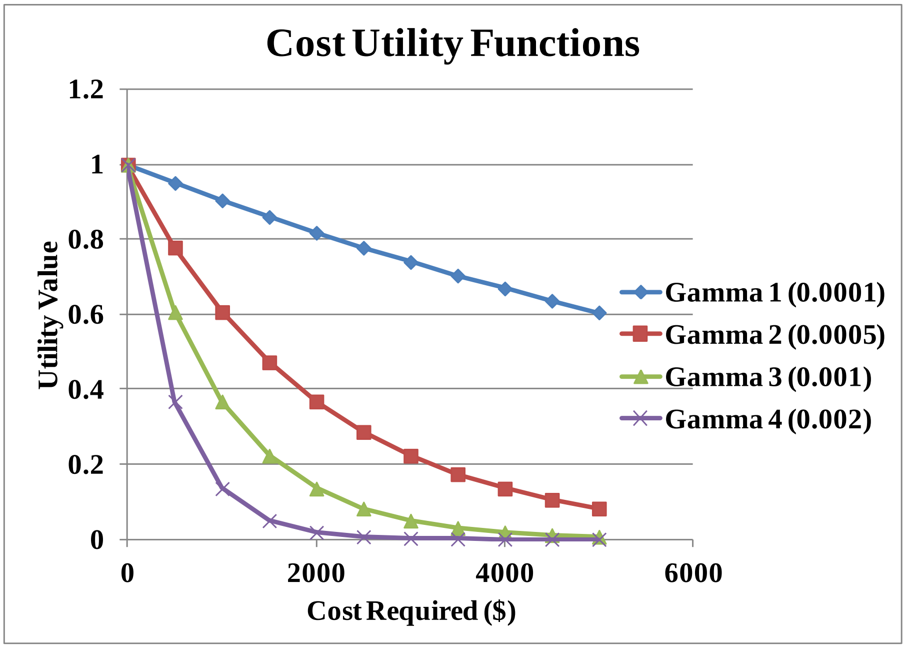


Figure 2.3 - Cost attribute utility function options

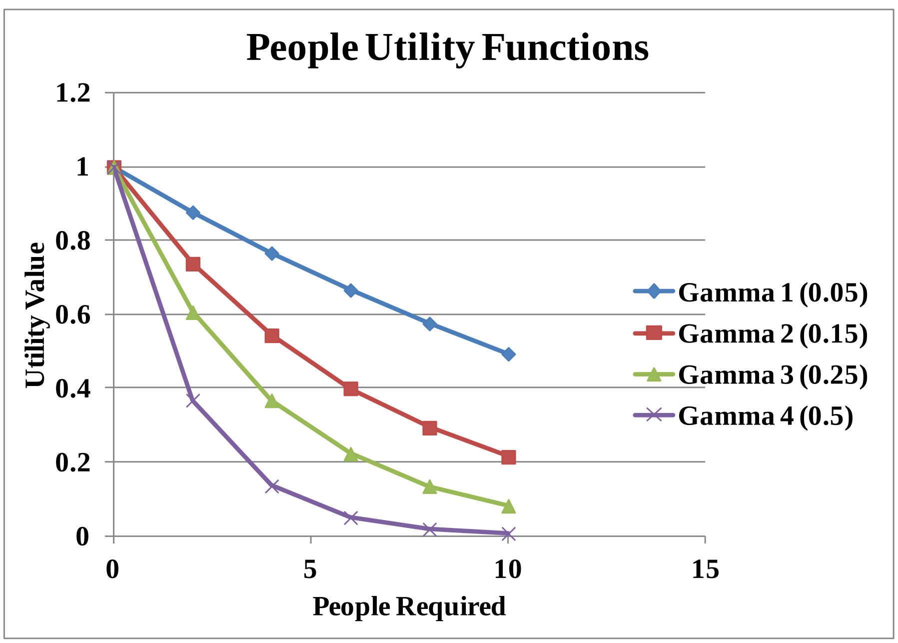


Figure 2.4 - People attribute utility function options

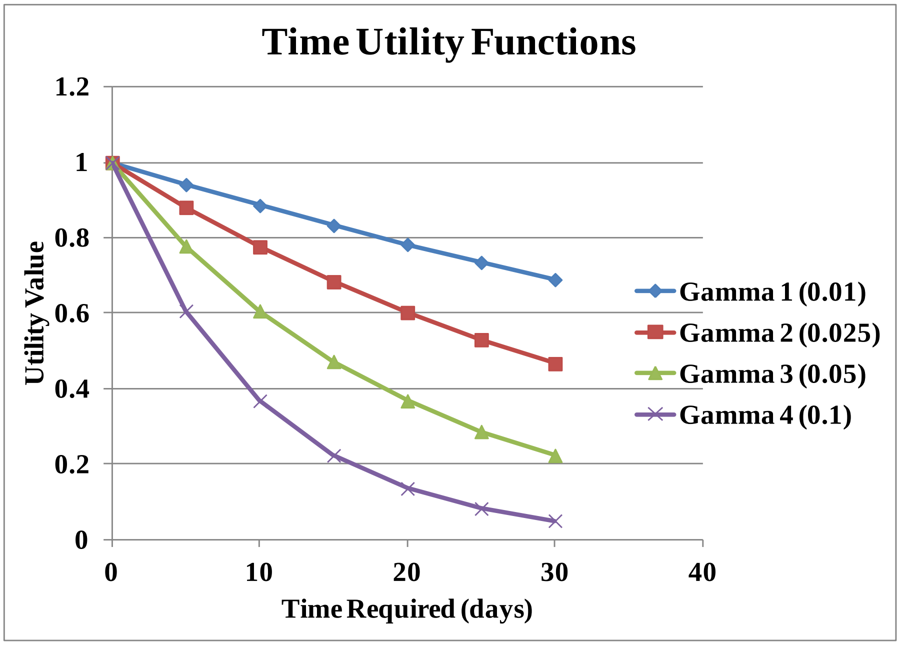
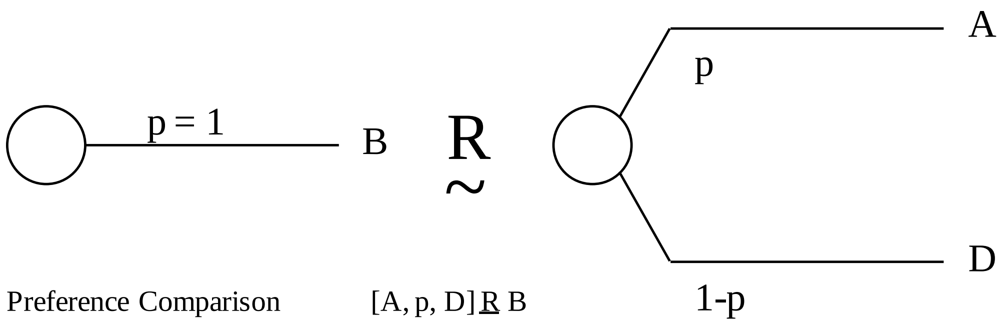


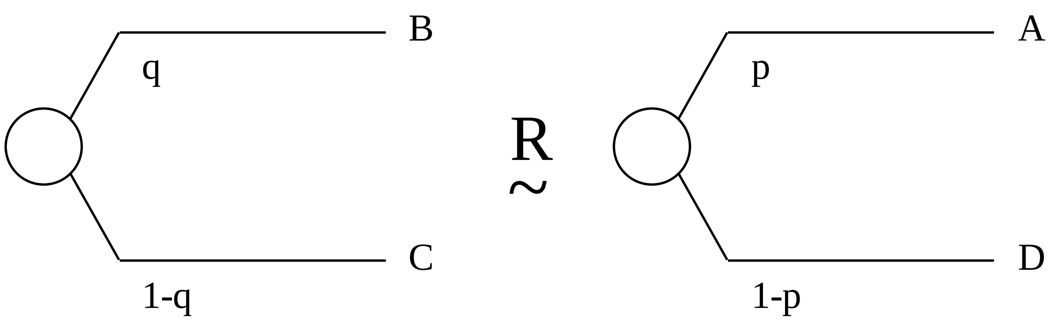
Figure 2.5 - Time attribute utility function options

The four utility function choices for each of the three attributes provide a starting point for determining the preference system of the user. To determine which function best describes a user's preference toward a certain attribute, industry applications typically ask the decision-maker questions in the format of the continuity axiom lottery of Table 2.3. There are many ways in which to ask these questions. The use of a single lottery system is called the Standard-Gamble method, whereas comparing two lottery scenarios is called a Paired-Gamble method. Assuming event A is the most preferred outcome, D is the least preferred, and events B and C fall in between A and D, Figure 2.6 and Figure 2.7 explain the difference between the two methods, including the manners in which the lottery question may be posed.[20]



1. Preference Comparison [A, p, D] R B
2. Probability Equivalence [A, p, D] ~ B (A › B › D)
3. Value Equivalence [A, p, D] ~ B
4. Certainty Equivalence [A, p, D] ~ B

Figure 2.6 - Standard-Gamble Method.[20]



1. Preference Comparison [A, p, D] R [B, q, C]
2. Probability Equivalence [A, p, D] ~ [B, q, C] ((A › B › C › D))
3. Value Equivalence [A, p, D] ~ [B, q, C]

Figure 2.7 - Paired-Gamble Method.[20]

The Standard-Gamble method relies upon the use of comparing a guaranteed outcome to the possibility of obtaining either the most preferred or the least preferred outcome. This is illustrated in Figure 2.6 where event A is the most preferred outcome and D is the least preferred. Event B falls somewhere in between the two such that, A ≻B≻D. The Preference Comparison technique provides a probability of this A-D lottery and requests the decision-maker to decide whether the lottery is more desirable than the guarantee of event B. This comparison is denoted by the equivalence expression, [A, p, D] $\underline{R}$ B. It is the preference, R, which is being determined by the user and is therefore represented by an underline in its equivalence expression.

The second comparison technique for the Standard-Gamble method is Probability Equivalence. In this scenario, it is the probability which is left for the user to determine and is thusly underlined in the expression, [A, $\underline{p}$, D] ~ B. What probability, p, would cause the user to be indifferent between a guarantee of event B and a possibility of the best or worst outcome? In other words, how likely would event A have to be before the user would accept a deal with a nonzero possibility of receiving their worst outcome?

Similarly, the Value Equivalence method asks the user for the Event A which, given the probability and other outcomes, would cause the user to be indifferent between a chance at Events A or D, or receiving event B for certain. Since this method requires the user to enter the event A, it is represented by the expression [$\underline{A}$, p, D] ~ B.

Finally, the Certainty Equivalence method asks the user for the event B which would make them indifferent between receiving B for certain and a chance at either event A or D. Event B therefore represents the user's certain equivalent for the lottery of a p probability for obtaining event A and a $(1 - p)$ probability of obtaining event D.

Similarly as with the Standard-Gamble method, the Paired-Gamble method uses a lottery system to obtain user outcome preferences. The Paired-Gamble method, however, uses a set of two lotteries and asks the decision-maker to compare the two scenarios with one of three methods: Preference Comparison, Probability Equivalence, or Value Equivalence. These three methods are identical to their Standard-Gamble relatives, only now there are two lottery scenarios to consider, as depicted in Figure 2.7. With two scenarios comes an additional event, event C. The preference order of these events is augmented to A ≻B≻C ≻D. The Preference Equivalence, denoted by [A, p, D] $\underline{R}$ [B, q, C], asks the user to identify which lottery they prefer. Would the user prefer a p probability chance at their best scenario, or a q probability of receiving the second-highest scenario? Both scenarios have a possibility of obtaining one of the least desirable outcomes. The Probability Equivalence scenario, denoted as [A, $\underline{p}$, D] ~ [B, q, C], asks the user for the probability p which would make them indifferent between the lottery of experiencing event A with probability p and event D with probability $1 - p$ or the lottery of experiencing event C with probability q and event D with probability $1 - q$. Finally, the Value Equivalence, represented as [$\underline{A}$, p, D] ~ [B, q, C], requests the user to identify the event A which would cause them to be indifferent between the same two scenarios.

As an example of each Standard-Gamble and Paired-Gamble situation, assume events A, B, C, and D are winning \$100, \$60, \$20, and \$0, respectively. Let the default p probability be 0.8 and the default q probability be 0.6; these are the p and q values unless the Gamble method requires the decision-maker to identify a probability. The Standard-Gamble Preference Comparison method asks the decision-maker to identify which lottery they prefer: (a) an 80% chance at winning \$100 and a 20% chance at winning nothing, or (b) a guaranteed win of \$60. The Probability Equivalence method asks a similar question, but requires the decision-maker to supply the probability of winning \$100 which would make them indifferent between this lottery and a guaranteed win of \$60. The Value Equivalence method returns to the default probability of 0.8 and asks the user to identify the outcome, with an 80% chance of winning, which would make them indifferent to a guaranteed win of \$60. The Certain Equivalence method asks the decision-maker to decide what their guaranteed win value is which would make them indifferent between the default lottery of 80% chance of winning \$100 and 20% chance of winning \$0. This value is called the certain equivalent.

The Paired-Gamble methods are only slightly different from the Standard-Gamble comparisons in that the lotteries now feature a comparison between two scenarios. The Preference Comparison method now asks the users to indicate which lottery is more favorable: (a) an 80% chance at winning \$100 and a 20% chance at winning \$0, or (b) a 60% chance at winning \$60 and a 40% chance at winning \$20. The purpose of these comparisons is to determine the risk attitude of the decision-maker. Clearly, lottery (a) has a higher risk with a higher reward, but does this accurately describe the risk attitude of the decision-maker? The Probability Equivalence method once again asks the decision-maker for the probability which makes them indifferent between the two lotteries: (a) a p probability of winning \$100 and a $(1-p)$ probability of winning \$20, or, (b) a 60% chance at winning \$60 and a 40% chance at winning \$20. Finally, the Value Equivalence method ask the decision-maker to indicate what outcome with an 80% chance of receiving would make them indifferent to a 60% chance at \$60 and a 40% chance at \$20.

The methods explained through example and summarized in Figure 2.6 and Figure 2.7 are a way in which to determine the decision-maker's preference system. The Preference Comparison Paired-Gamble method is used in the Decision Advisor software tool to establish the risk attitude of the user with regard to the individual attributes of cost, people, and time resources. The Probability Equivalence Standard-Gamble method is used to ascertain the manner in which the user is willing to trade worse outcomes of two individual attributes for a better outcome of the remaining attribute. The specific applications of these methods to the analysis of mitigation techniques are described in Chapter 5.

This chapter has provided a mathematical background for understanding both of the software tools created during this research. The utility theory and decision analysis material will be used in Chapter 5 with the Decision Advisor Tool. In the next two chapters, General Error Regression, as discussed in Section 2.2, is applied to the problem of small satellite risk management via the CubeSat Risk Analysis software tool.

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Chapter 3: CubeSat Risk Analysis Software Tool

The CubeSat Risk Analysis Software Tool and its Risk Estimating Relationship (RER) algorithm relies heavily on the mathematical foundation described in Chapter 2. The concept of using the same methodology as cost models was a result of the author's Master's Thesis work with cost and reusability of CubeSat missions.[1] Cost Estimating Relationships (CERs), while not perfectly accurate, do provide a general idea of the costs associated with a mission. This allows easier comparison between missions for funding or other purposes. Similarly, developing RERs would allow users to compare missions in terms of risk levels. So, the basis of the RER development was the same as that of the CERs, General Error Regression, as described in Chapter 2.

Although the General Error Regression technique is found in the development of many industry-used cost models,[2,3] with cost models, the cost is a known quantity – both in concept and in value. For the risk likelihood and consequence values to be analyzed in this research, CubeSat mission data needed to be first defined, then gathered, and ultimately processed for use in creating the RER derivations and for display within the risk analysis software tool. This chapter will describe the processes of gathering and analyzing data to obtain the Likelihood and Consequence Estimating Relationships, LER and CqER, respectively, as well as the integration of the CubeSat Risk Analysis Software Tool.

3.1 Survey Creation and Data Gathering

Industry methods of managing and discussing mission risks typically reference Likelihood and Consequence scales similar to those given in Table 3.1 and Table 3.2, respectively.[4,5,6] While a low-cost CubeSat Risk Management Plan has been established in prior work, the primary recommendation of that work was to replace the subjective Likelihood and Consequence scales with more objective scales that are based on historical and statistical analysis.[7]

Table 3.1 - DoD likelihood criteria for risk ranking

Level	Likelihood	Probability of occurrence
1	Not Likely	~10%
2	Low Likelihood	~30%
3	Likely	~50%
4	Highly Likely	~70%
5	Near Certainty	~90%

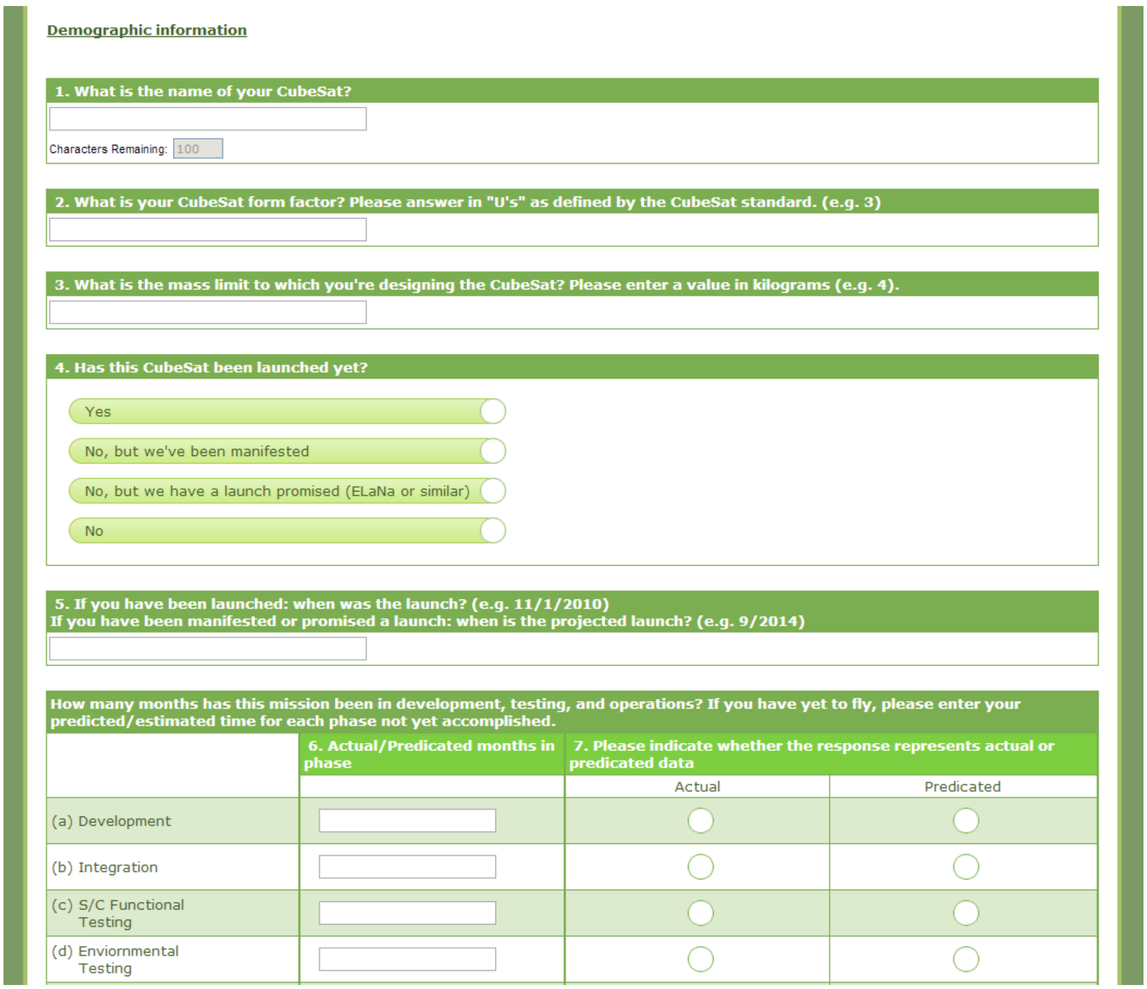
Table 3.2 - DoD consequence criteria for risk ranking

Level	Technical	Schedule	Cost
1	Minimal or no consequence to technical performance	Minimal or no impact	Minimal or no impact
2	Minor reduction in technical performance or supportability, can be tolerated with little or no impact on program	Able to meet key dates.	Budget increase or unit production cost increases (1% of budget)
3	Moderate reduction in technical performance or supportability with limited impact on program objectives	Minor schedule slip. Able to meet key milestones with no schedule float.	Budget increase or unit production cost increases (5% of budget)
4	Significant degradation in technical performance or major shortfall in supportability; may jeopardize program success	Program critical path affected.	Budget increase or unit production increase (10% budget)
5	Severe degradation in technical performance; cannot meet key technical/supportability threshold; will jeopardize program success	Cannot meet key program milestones.	Exceeds budget threshold (10 % of budget)

In order to achieve this historical and statistical analysis, it was necessary to collect data on current and past CubeSat missions. No collection of historical mission data for CubeSats previously existed that could be used for risk analysis, so an empirical data set was collected as part of this research. The collection of this data began in April 2013 at the CubeSat Developers Workshop in San Luis Obispo, California.[8]

When initially developing the CubeSat Mission Risk Survey, several considerations were made. It was important to have a survey which respondents could complete within 15-30 minutes and yet provide adequate information for analysis. Therefore, a proper balance was needed in terms of the number and depth of questions. The survey was also formatted so respondents could save their responses and continue later, in case of meetings, classes, or needing to find the appropriate information for accurate answers. It was desired that as many responses as possible be obtained, as such an easy-to-use and mobile-ready platform was preferred. There are many existing survey sites which offer these benefits, however, not all of these sites offer free access. Some sites offer student trial versions, but only one student version is equivalent to the full professional version. So, the CubeSat Mission Risk Survey was built on SoGoSurvey.com. This website allows save and continue options, mobile-ready surveys, and plenty of different types of question formats.

The CubeSat Mission Risk Survey is an online form, shown in Figure 3.1, where mission developers can input information regarding their CubeSat missions. The questions are categorized into demographic information and risk events. After inputting basic demographic information, satellite designers submit the consequence values of any events they experienced during the design, integration and testing, and operations of their spacecraft. The spacecraft designers are requested to use the DoD consequence scale given in Table 3.2; in this way all responses are based on the same relative scale. It is acknowledged, however, that there is still a level of subjectivity in the response of the experts. Having multiple responses per mission is useful, as it can help remove survey bias and achieve a more accurate set of response values. The information types recorded in the survey are outlined in Table 3.3. This data is processed through the analysis and risk estimating relationship algorithms described in the following sections.


Demographic information

1. What is the name of your CubeSat?

Characters Remaining: 100

2. What is your CubeSat form factor? Please answer in "U's" as defined by the CubeSat standard. (e.g. 3)

3. What is the mass limit to which you're designing the CubeSat? Please enter a value in kilograms (e.g. 4).

4. Has this CubeSat been launched yet?

- Yes
- No, but we've been manifested
- No, but we have a launch promised (ELaNa or similar)
- No

5. If you have been launched: when was the launch? (e.g. 11/1/2010)
If you have been manifested or promised a launch: when is the projected launch? (e.g. 9/2014)

How many months has this mission been in development, testing, and operations? If you have yet to fly, please enter your predicted/estimated time for each phase not yet accomplished.

	6. Actual/Predicated months in phase	7. Please indicate whether the response represents actual or predicated data	
		Actual	Predicated
(a) Development			
(b) Integration			
(c) S/C Functional Testing			
(d) Enviornmental Testing			

Figure 3.1 - CubeSat Mission Risk Survey

Table 3.3 - Survey information

Demographic information (Factor of Interest)	Risk root cause information
• Mission name • Mission form factor • Mass limit • Mission success designator • Respondent years experience • Respondent role on team • Funding level of mission • Launch situation • Launch date • Life-cycle months • Institution responsible • Team demographic breakdown	• Schedule risk events • Payload risk events • Spacecraft communication risk events • Spacecraft health data risk events • Spacecraft standards risk events • Personnel and management risk events • Cost risk events

Several levels of user testing were completed on the survey before asking the broader CubeSat user community to supply their responses. The first round of testing was completed on UT-Austin TSL members to determine if the survey was easy to use and understand as well as work out any initial issues. Then, trusted academic collaborators were asked for their input as well. As part of the testing process, it was determined that a companion guide should be created to help users navigate the survey. This companion guide can be downloaded directly from the survey site, or from the author's research website. The guide provides more information regarding why the question is being asked, and what type of answer is requested of the respondent.

3.2 SURVEY DATA ANALYSIS

The CubeSat Mission Risk Survey results were collected from April through November 2013. Several attempts were made to solicit responses at conferences and in publications. The total number of responses was 66, with 11 missions having more than one response, one mission did not conform to the CubeSat standard and was thus removed from consideration, and two responses did not provide enough information to warrant including the data in regression analysis. With these considerations, 52 unique missions were represented in the survey.

During initial analysis, three missions were consistent outliers when compared with the other data by plotting a series of root cause values against the factors of interest to determine possible regression equations. It was assumed that the missions were outliers based on the large form factor of one mission, and the extremely small values submitted for the life-cycle time periods of the other two missions. A trade study was completed to determine whether removing each mission would decrease the SSD values significantly. Results showed that removing the three missions simultaneously decreased 61 of the 68 root cause SSD values, yielding an average reduction of the model squared deviations by 8.43%. Thus, these three missions were removed from consideration, though their demographic information is included in the following high-level analysis.

The majority of missions represented were 3U CubeSats (29 missions) with the next most common form factor being 1U missions (16). Note that the one mission which did not follow the CubeSat standard was removed from high-level analysis. The survey asked whether the mission had launched, giving the options listed in Table 3.4. The most frequent response showed that the mission not yet launched but had been manifested at the time of survey response. Respondents were able to select multiple roles and subsystems in which they participated on the mission. These roles are shown graphically in Figure 3.2 and Figure 3.3. Additionally, respondents were asked to indicate how many years experience they have working on spacecraft. The majority of respondents (38) said they had between one and five years experience. The other categories, 0-1, 5-10, 10-15, 15-20, and >20, each had between 3-7 responses per category. For type of funding, respondents were also allowed to indicate more than one option and these results, along with the total amount of funding, are shown in Table 3.5. Figure 3.4 shows the breakdown of team demographic information. The x-axis represents the percentage of the team in a certain category while the y-axis represents the number of responses in that category. For example, the first bin shows 31 survey responses indicated their team was comprised of 0-25% professionals while 14 responses indicated 0-25% undergraduate and 26 responses show 0-25% graduate student involvement. Figure 3.5 illustrates the broad spectrum of managing organizations – from only universities to conglomerate relationships between universities, corporations, and government.

Table 3.4 - Responses to launch questions

No	10
No, but a launch has been promised (ELaNa or similar)	13
No, but satellite has been manifested for launch	28
Yes	14
Total	**65**

Table 3.5 - Type and amount of funding

Type of Funding	Count	Amount of Funding	Count
Internal funding	44	(0,50K]	7
Non-Competitive award	18	(50K,100K]	3
Competitive award	53	(100K,300K]	9
Grant & Sponsorship	6	(300K,500K]	5
		(500K, 1M]	6
		(1M, 5M]	9
		>5M	1
		Blank & N/A	25

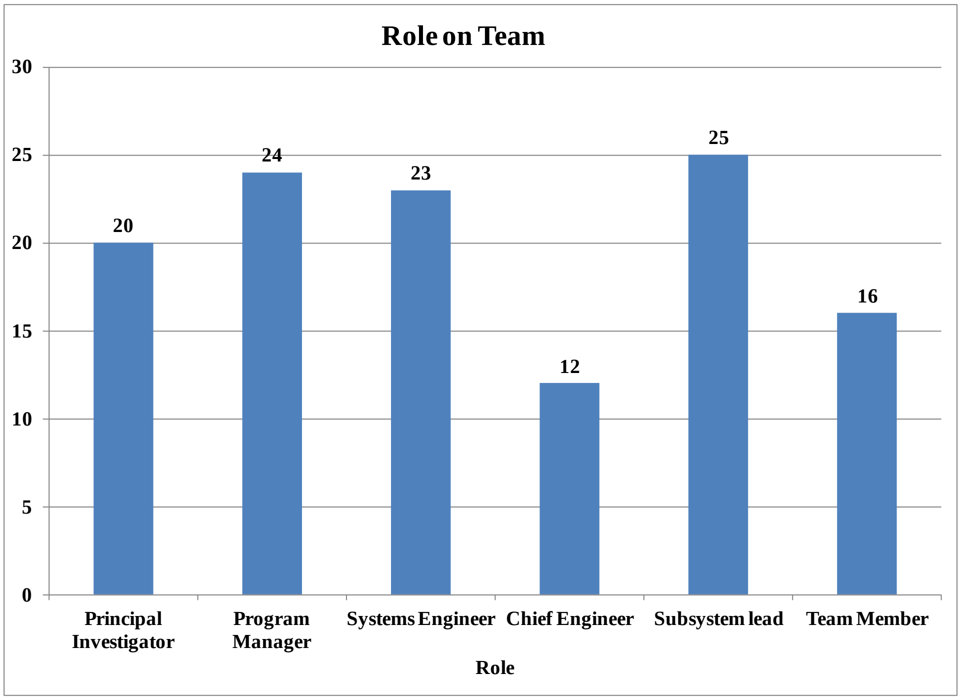


Figure 3.2 - Response to role on team

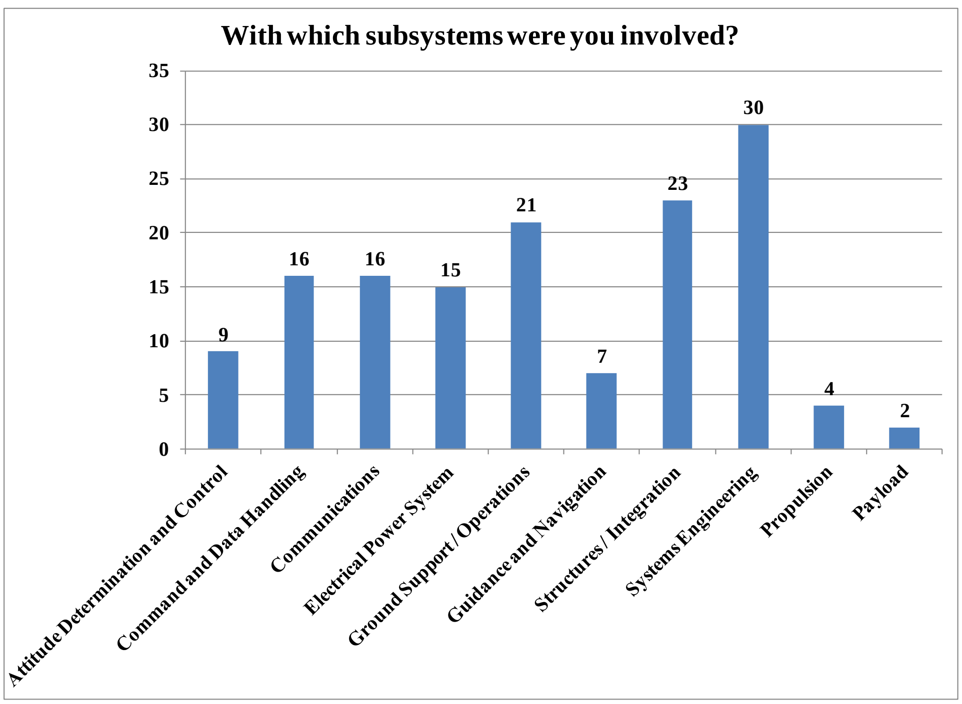


Figure 3.3 - Response to subsystem involvement

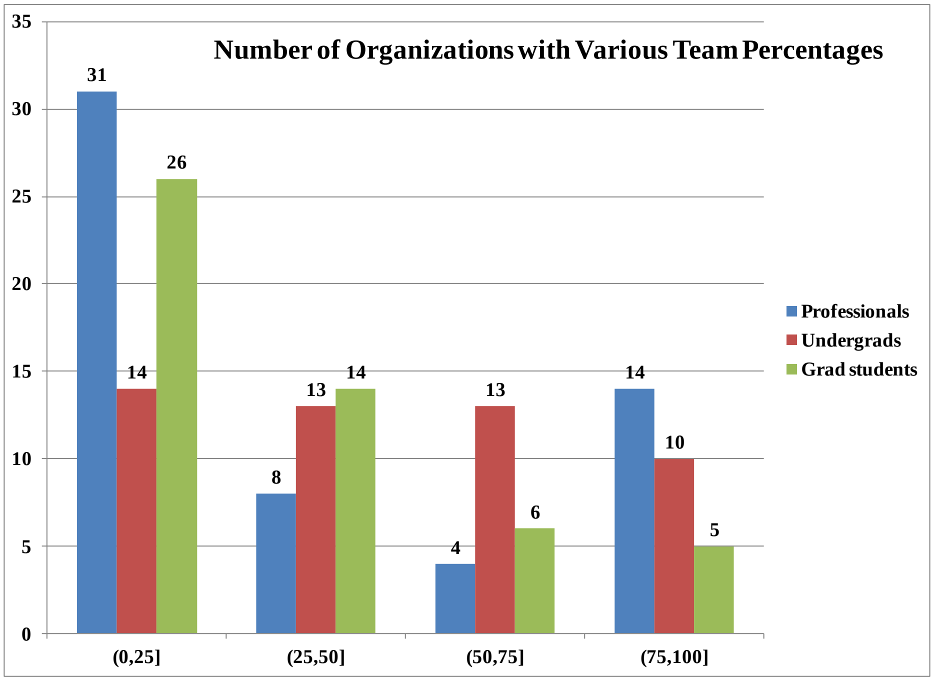


Figure 3.4 - Team demographic percentages

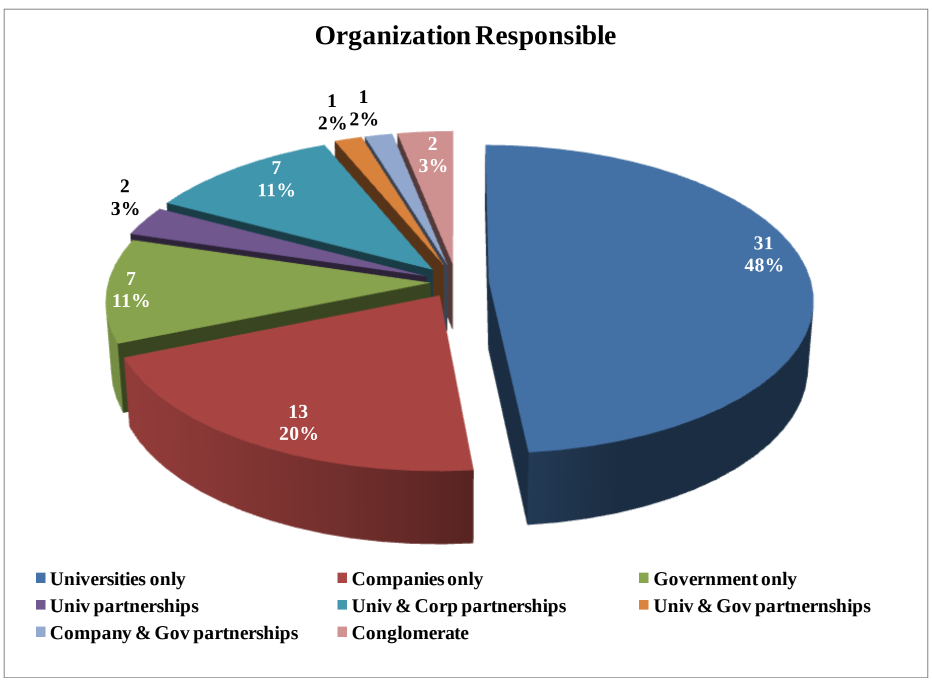


Figure 3.5 - Organization responsible

3.3 Data Processing Algorithms

The data gathered from the CubeSat Mission Risk Survey went through a series of processing algorithms prior to being inputted into the software tool. The raw data first went through pre-processing to ensure the file was in proper format for data analysis. Additionally, the processing computer code transformed the launch and role responses from text to numerical values, combined the life-cycle estimates, generated the likelihood values, converted the risk text entries to numerical values, and combined the multiple responses to a single record per mission. Each of these steps is more fully described in the following sections.

3.3.1 Pre-Processing Algorithms

The raw data obtained from the risk survey often had data that was not properly formatted – such as mass, form factor, life-cycle months, or launch date. Thus, a major concern was formatting all these data in the format the processing code expected, which primarily consisted of removing units. Additionally, with multiple responses per mission, it was imperative to label the same missions with the same mission number. With the ability to select multiple roles on the team, including "other", it was necessary to record what the respondent's "other" role was with regards to the primary options. In some cases, if the entry did not provide the key factors of interest or was not in the CubeSat form factor, then it was removed from consideration prior to running the processing algorithms.

3.3.2 Launch and Role Processing Algorithms

To indicate whether or not the CubeSat mission had launched, respondents were given text options. These text responses were then transformed into numerical values. As a baseline, if the response indicated "No" it was given a value of 4; "No, but we have been promised a launch" was given a value of 3; "No, but we've been manifested" was given a value of 2; "Yes" was given a value of 1. These values were chosen because the RER function forms use the Launch variable as a multiplier. If the launch response was "yes", it should have a lower risk because most of the risk had been reduced by the time of launch.

A trade study was completed to see how the data would be impacted by changing the numerical mapping scheme. The baseline and three sets of trial launch variable values are presented in Table 3.6. Each test case was used as the launch variable values during the regression analysis. The trial which produced the lowest SSD values, and thusly optimized the regression routine, was selected as the most appropriate launch response to numeric value mapping scheme. It is acknowledged that there are an infinite number of possible mapping schemes, but the values of Table 3.6 provided an initial assessment. The results, in fact, showed that the baseline was a good assumption. It is left as future work to expand upon the trials to find a better set of launch choice values. A more detailed account of the trade study analysis is given in Chapter 4, Section 4.2.

Table 3.6 - Launch choice trade study values

Response	**Baseline value**	**Trial 1 value**	**Trial 2 value**	**Trial 3 value**
No	4	1	2	1
No, promised launch	3	2	1.75	1.5
No, manifested	2	3	1.5	1.75
Yes	1	4	1	2

The risk survey also asked each respondent to indicate their role on the team. The role information was used to combine multiple responses for the same mission, if necessary, as well as for the high-level demographic analysis which was presented in the previous section. A processing algorithm searched through the raw data and counted how many roles each respondent indicated in their response. For each role selected, they gained a certain weighted value as shown in Table 3.7. Some respondents indicated multiple roles, and therefore increased their weight. This is appropriate because the role value is only used during the combination of experts. Thus, the response of someone who had multiple roles in their mission will weigh more than someone who had a single role. It is acknowledged that this method represents one of many possible ways of combining responses. Future iterations of this analysis could investigate alternative methods.

The weights were initially designed with the most knowledgeable person receiving a "1" and the next most knowledgeable people receiving a certain percentage of the top value. The use of percentages was chosen for easy conceptualization. Since the values are based on percentages, a trade study could easily determine whether scaling the values has any impact on the utility curve (to be described later) and the fit to the data. However, this is left as a future study.

The role values used in this analysis are based on experience with regard to the amount of knowledge such a team member would be able to provide during the entire mission. A trade study was completed to analyze alternative percentage-based role value schemes with the maximum still being "100%". In an identical method to the launch choice value trade study, this trade study changed the role values according to the trial cases listed in Table 3.7, re-ran the General Error Regression method to obtain new risk estimating relationships, and compared the SSD values between the baseline and trial role value schemes. The study found that the Trial 3 values in Table 3.7 provided lower SSD values than alternative schemes, and therefore better represented the survey data. A more detailed account of the trade study analysis is given in Chapter 4, Section 4.2. The role values of Table 3.7 make some intuitive sense, as the program or project manager is most familiar with the technical, cost, and programmatic issues of the spacecraft. The systems and chief engineers are most familiar with the technical issues, and thus receive a smaller role value. The Principal Investigator is included in all technical, cost, and programmatic discussions, but may not be as familiar with the details as the program manager. The subsystem lead and subsystem members are typically familiar with only their subsystem, and therefore receive a smaller role value than the systems or chief engineer.

Table 3.7 - Respondent role to value trade study options

Role	Baseline Value (%)	Trial 1 (%)	Trial 2 (%)	Trial 3 (%)
Principal Investigator	50	100	15	50
Program/Project Manager	100	50	100	100
Systems Engineer	75	75	50	75
Chief Engineer	75	75	50	75
Subsystem Lead	25	25	25	25
Subsystem Member	5 per subsystem	5 per subsystem	5 per subsystem	5 per subsystem

3.3.3 Combining life-cycle estimates

The CubeSat Mission Risk Survey asked for time durations (months) of six key phases of the mission life-cycle: development, integration, spacecraft functional testing, spacecraft environmental testing, waiting for a launch, and operations. The survey asked respondents to indicate with their estimates of time spent in each mission life-cycle phase whether the response was an actual or predicted value. For analysis purposes, however, it was necessary to resolve the differences between actual and estimated event durations and transform these estimates to a common scale.

Because missions tend to overrun estimated life-cycle durations, it is assumed that if the response specifies a predicted value, the actual duration value will be larger than indicated. Furthermore, as the mission predicts time durations further away from the current phase of the mission the estimate is expected to compound exponentially over time. For this reason, the time durations specified in the survey responses were modeled by Equation (3.1). In this equation, j is an index representing the current life-cycle phase of analysis and $act.last$ represents the last time index with an actual value. If the life-cycle phase index under consideration is the same as the last actual time value, then the common time is identical to the predicted time as one would expect.

$$t_{common} = 1.25^{j-act.last} * t_{predicted} \tag{3.1}$$

The root factor value of 1.25 was found to be the most appropriate value to mathematically describe the mission life-cycle time estimate growth as the estimated time moves away from the last actual reported value. Through a similar trade study to that of the launch and role value studies mentioned in the previous sections, the factor value of 1.25 was compared against the four alternatives given in Table 3.8. The trial values were used in the regression analysis, and the resulting SSD values compared to the baseline case. Compared to the other values, a factor value of 1.25 was found to be the best assumption, because the other values did not provide a significant improvement. As with the other trade studies, the values tested here are but a small subset of possible schemes. A more detailed account of the trade study analysis is given in Chapter 4, Section 4.2.

Table 3.8 - Life-cycle factor trade study options.

	Baseline	Trial 1	Trial 2	Trial 3	Trial 4
Value	1.25	1	1.5	1.75	2

3.3.4 Likelihood Value and Text N/A Generation

The CubeSat Mission Risk Survey only asked for the consequence values associated with each mission risk and their associated root causes. As previously discussed, the mission risk is the event that could happen which may jeopardize the mission, and the root causes are the methods by which this event could happen.[7] It was assumed that if a consequence value was submitted for a root cause, then the event happened, and thus was given a likelihood value of 5 based on the DoD scale of Table 3.1. However, if the response for the root cause was “Does not apply”, “Did not experience”, “Did not include in spacecraft design”, or “Included in spacecraft design, but event did not occur”, then the likelihood was given a value of 1. If the textual response indicated “Have not reached this phase yet”, then the likelihood was assigned the value of 3, since it was still likely the mission might encounter the given event. These textual responses were nicknamed the “special values” and were used to give the root cause consequence values a numerical representation. The mapping of these “special values” is the last step prior to the combination of experts algorithm. After combining experts, the data is fully processed and may be analyzed in regression analysis and input into the risk management tool.

3.3.5 Combining Experts

Having more than one response for each mission allowed for validation and calibration of the values submitted. With multiple responses per mission, however, it became necessary to normalize and process the associated responses, so as not to double count missions in the RER formulation. The field of Decision Analysis has developed methods of combining expert opinions and information through the use of Bayes' Theorem, and combining prior probability distributions.[9,10,11] This method is not valid for the values obtained through the risk survey. It is not appropriate to overlay probability distributions on probability assessments as given in the risk survey responses, and as such, Bayesian inference methods do not apply in this situation. Instead, another concept from Decision Analysis was used – the utility curve.[12]

An initial, common-sense approach for combining multiple expert opinions is to use a weighted average of responses. The question then becomes how to obtain the weights for each response while maintaining a measure of objectivity. Because of its mathematical form, the utility curve (u-curve) was chosen as the method of obtaining the weights for the weighted average combination of expert responses. The u-curve allows an input of multiple parameters, such as a respondent's role and years of experience, and yields a singular output of the overall response value. Because of the multiple inputs, it was necessary to previously define the role value scheme prior to the u-curve function definition. The only subjectivity introduced in this development is the choice of utility function and parameters. The appropriate response parameters are then processed through the u-curve formula to obtain a utility value (u-value) for each response. A higher u-value indicates more importance associated with the expert response, and will thus yield a higher weight in the combined calculation. These u-values are normalized to yield weights associated with each response; the input parameter values were not previously weighted. A combined root cause response for the mission designator is then given by the weighted average of the root cause response values. Because the mass, form factor, launch, and launch date should not differ between expert responses of the same mission, the values are not combined, but rather stored from the response associated with the higher u-value. This choice has no special significance other than the higher u-value indicates the more expert opinion. Finally, missions with multiple responses are removed and replaced by their combined response. This process of combining expert responses is illustrated in Figure 3.6.

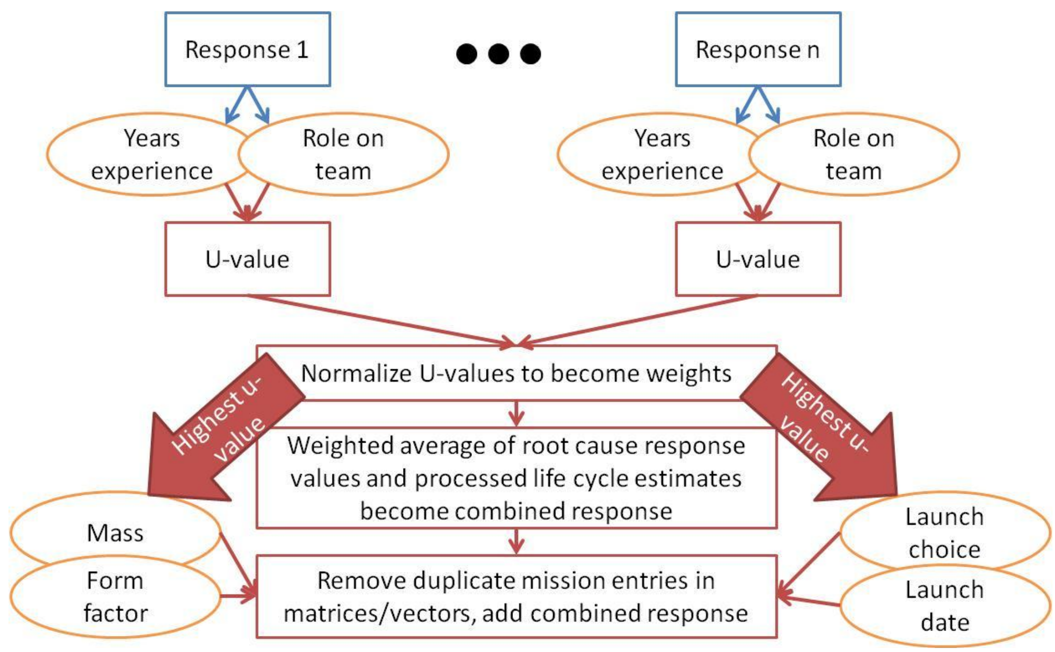


Figure 3.6 - Combining experts initial algorithm

The u-curve function is based on the demographic information available in the CubeSat Mission Risk Survey. Namely, this includes the number of years of experience and the role of the respondent on the team. The selected u-curve function, tested through trade studies and determined to provide the best-fitting curve, is given in Equation (3.2) and the function is plotted pre-normalization in Figure 3.7 for a range of experience years and role values. Note that the role values input into the utility curve are in decimal form and not the percentage format of Table 3.7. A total of six different u-curves were compared in the trade study by the SSD of the derived risk estimating relationships. The six equations are listed in Table 3.9. With 68 total SSD values, the values which were decreased by changing the u-curve function indicated that the new u-curve function fit the data better than the baseline function. Future iterations of this trade study could include different utility curve functions in the analysis. A more detailed account of the trade study analysis is given in Chapter 4, Section 4.2.

$$U(role, years) = years^{\frac{1}{4}} + role^{\frac{1}{6}} \tag{3.2}$$

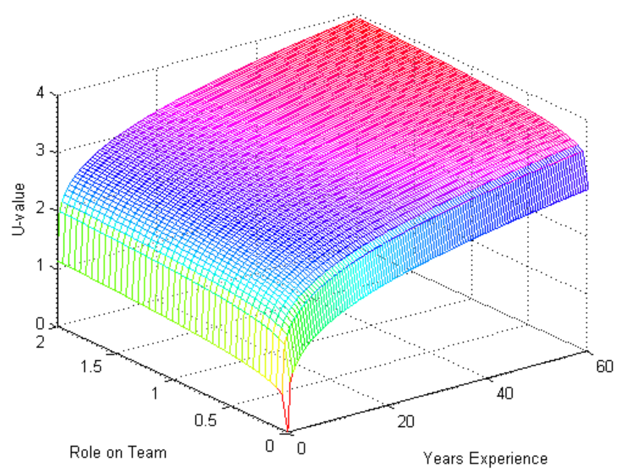


Figure 3.7 - Plot of un-normalized u-curve function

Table 3.9 - Combining experts trade study options.

Trial	Equation
Baseline	$ucurve = \log(0.5 * yrs * role + 1)$
Trial 1	$ucurve = yrs^{1/4} + role^{1/6}$
Trial 2	$ucurve = \log(yrs^{(0.1*role)} + 1)$
Trial 3	$ucurve = 0.05 * (role + yrs)$
Trial 4	$ucurve = 0.3 * (yrs^{\frac{1}{2}} + role^{\frac{1}{3}})$
Trial 5	$ucurve = (yrs + role)^{1/12}$

It is assumed that the more years of experience and more involved role the respondent has, the more valuable their information is in the combination of experts algorithm. Additionally, it is assumed that with slightly more experience both in years and role on the mission team, vastly more knowledge is obtained. In the university satellite lab, this characteristic is referred to as the "steep learning curve." For these two reasons, the u-curve function Equation (3.2) takes the shape and form that it does. Recall that the u-values are normalized between the responses of the same mission. While the number of years of experience is self-explanatory, the respondent's role on the team is described in Section 3.3.2 and detailed in Table 3.7.

3.4 GENERAL ERROR REGRESSION APPLICATION

Related research, using the general risk management plan described in Chapter 1, identified seven separate mission risks, each with between four and seven root causes.[7] With both consequence and likelihood to calculate, there are 68 total root causes. Twelve function forms, listed in Table 3.10, were studied for each root cause – one for the

Likelihood Estimating Relationship (LER) and one for the Consequence Estimating Relationship (CqER). In these equations, the letter variables correspond to the coefficients of the function while the factors of interest are the form factor (ff), whether or not the mission has launched (launch), and the time spent in development (dev), integration (int), spacecraft functional testing (scfunc), environmental testing (environ), waiting for launch (wait), and operations (ops).

The SSD and R^2 values, described in Chapter 2, were calculated for each function. An Excel Macro implemented the Excel Solver function to minimize the SSD while holding the bias equal to zero for each of the function forms of the given root cause. Figure 3.8 shows the Excel spreadsheet for one of the root causes of a particular mission risk. The spreadsheet ranks the SSD values from lowest to highest, and the generalized R^2 value from highest to lowest, since it is desired to have a low SSD and a high R^2. To eliminate function forms with low SSD values, but also low R^2 values, a combined rank score was established. This combined rank score determines the function form that is most representative of the data, and will thus be used as the risk estimating relationship for the given root cause. In the special case that the R^2 value was determined to be unrealistically low, the next best function was selected, based on combined rank. If there was a tie between functions, the function with the lowest SSD value was selected. The number of times a function was chosen as the likelihood or consequence relationship is shown in Figure 3.9, with the function number corresponding to the entries listed in Table 3.10.

Table 3.10 - Risk Estimating Relationship Function Forms

(1) L1 = a + b*ff
(2) L2 = a + b*ff + cc*dev + d*int + e*scfunc + f*environ + g*wait + h*ops
(3) L3 = a + b*ff + cc*launch
(4) L4 = a + b*launch
(5) L5 = a + b*dev + cc*int + d*scfunc + e*environ + f*wait + g*ops
(6) E1 = a + b*cc^ff
(7) E2 = a + b*cc^launch
(8) E3 = a + b*cc^(dev+int+scfunc+environ+wait+ops)
(9) T1 = a + b*ff^cc
(10) T2 = a + b*dev^cc + d*int^e + f*scfunc^g + h*environ^I + j*wait^k + l*ops^m
(11) T3 = a + b*launch^cc
(12) T4 = a + b*ff^cc + d*launch^e

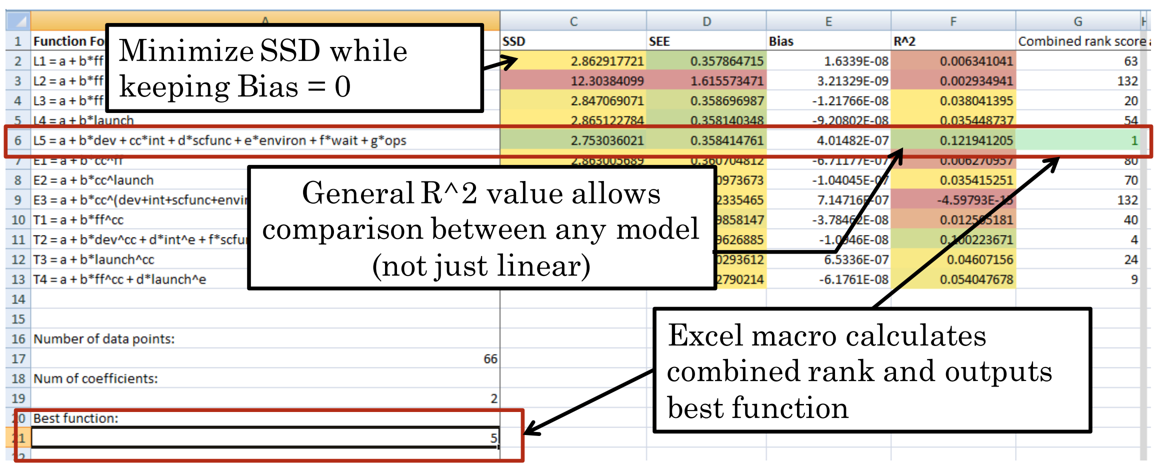


Figure 3.8 - General Error Regression implementation

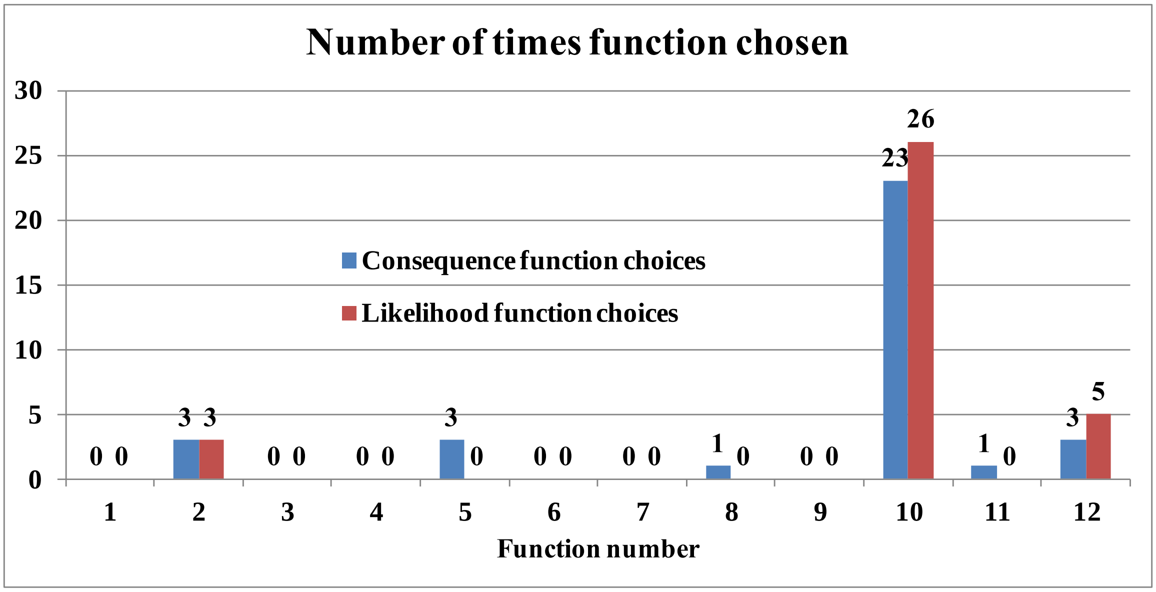


Figure 3.9 - RER function selections

Interestingly, the most chosen function by the algorithm, function 10, used only life-cycle development times as the input factors. This indicates that the risk likelihood and consequence values mostly relied upon the development cycle, and not necessarily on the form factor or whether or not the mission has launched. A quick look at the data results of Section 3.2 shows that most missions included in this analysis had not yet launched at the time of the survey, so the fact that the launch indicator does not play a significant role in the risk estimating relationships makes intuitive sense. However, it is interesting to note that function 10 did not universally represent all root cause consequence and likelihood values. In some cases, launch and form factor were important input factors, as is the case with functions 2 and 12. Other than the four root causes associated with the spacecraft standards risk which were found to use function 12 as the best fit, there was no clear pattern between which root causes were best described by including the form factor and launch indicator factors of interest.

3.5 SOFTWARE TOOL INTEGRATION

Experiences in the Texas Spacecraft Lab, and conversations with other university and low-cost CubeSat missions, showed that the creation of a risk management tool would be valuable to the CubeSat designer community. This tool needed to be easily accessible to provide benefit to those who wish to use it. As such, using common software like Excel to create the tool is ideal. Also making the tool easy to understand and use is a necessity. Based on previous research completed studying various types of cost models and their application to CubeSat missions, it was determined that a tool similar in design to existing cost models is optimal for the purposes of low-cost risk management.[1] The tool created in this analysis includes mission inputs, outputs, and plots pages, where the traditional 5x5 Likelihood-Consequence chart is displayed, as well as two pages listing the equations and coefficients chosen for each consequence and likelihood root cause. The only actions a user must perform to use the tool are to enter their mission input values on the inputs page and select their calculation and plotting methods. The output and function pages are calculated automatically. A User's Guide exists to help users navigate and understand the intricacies of the software tool. This User's Guide, along with a request to obtain the tool can be found on the author's risk research website.*

3.5.1 Inputs page

Existing cost model tools typically have an area for the user to input various parameters.[2,3] This inputs page is considered a necessity for the development of the risk management tool in an effort to make the tool as user-friendly as possible. For the

* https://sites.google.com/site/brumbaughresearch/

CubeSat Risk Analysis tool, the mission designer has to input their satellite form factor and mass, select a launch option from four choices, input their launch date, and input the months in development, integration, functional testing, environmental testing, awaiting launch, and operations. The internal calculations of the tool will then output the root cause likelihood and consequence values on the outputs page. This inputs page is shown in Figure 3.10. The user also has the ability to track the spacecraft risks at multiple milestones by indicating on the Options bar to which milestone the current inputs correspond. Then, the user may submit another set of inputs for a different milestone. Currently, up to three milestones may be tracked at a given time.

Note that other details such as the mission success, objectives, and budget are not included. For the purposes of initial regression analysis, the factors of interest were limited to those which were provided by all responses in the same format and included little subjectivity. To include a mission success indicator, difficulty scale to rank the objectives, or budget indicator would be to introduce another level of subjectivity since the survey responses were in an inconsistent text format for these questions. Additionally, providing a mission success evaluation is inherently subjective and biased based on the respondent's role on the project. Moreover, many fewer responses provided the necessary information to analyze these details than compared to the objective indications of form factor, life-cycle development, and launch indication. It is left as a future implementation to incorporate more factors into the regression analysis based on the needs of the community.

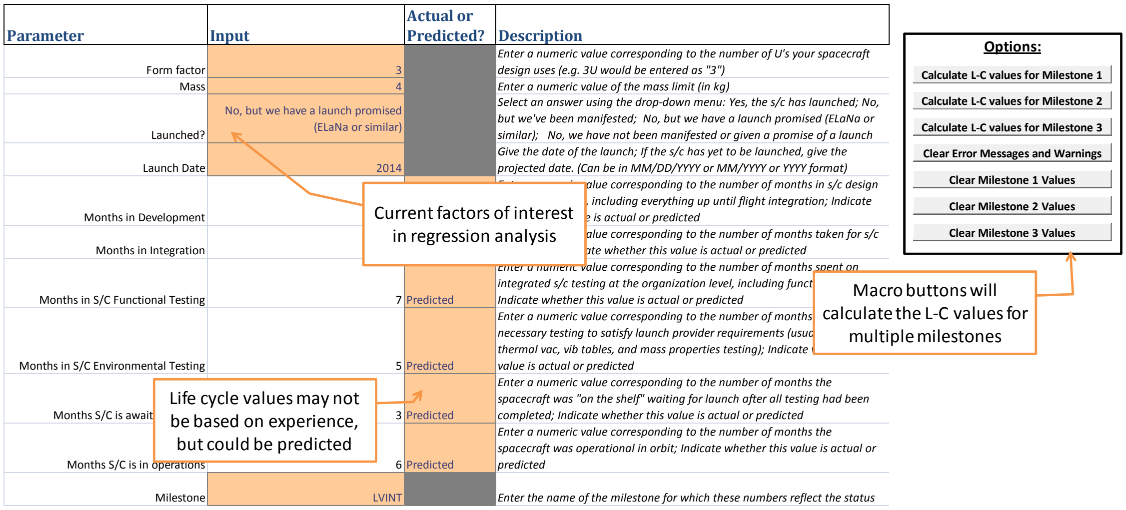


Figure 3.10 - Risk Tool Inputs page

3.5.2 Outputs page

Once the option to calculate the L-C values is selected, a Visual Basics for Applications (VBA) program takes the user-provided inputs and calculates the consequence and likelihood values for each root cause based on the formulas established from the regression analysis mentioned in the previous section to yield the outputs page similar to those shown in Figure 3.11. If the user has selected to track multiple milestones, additional columns are used to represent the spacecraft risk status at these additional milestones. Currently, the tool can only track three milestones at a time. If a user wishes to track more than three, they will need to use multiple versions of the tool, or run the tool multiple times. A future version of the tool may allow for tracking more than three milestones at a time. There are separate details pages which provide the selected formulas and associated coefficients for user reference. Note that because the data for each root cause is different, the coefficients are different for every function. Once the root cause likelihood-consequence (L-C) values have been calculated, the mission risk L-C is established through a weighted average of the root cause values using the rank reciprocal method to determine the weights.[7] It is acknowledged that the rank reciprocal method is one of many weighting methods available, and future iterations of the tool may include options for the user to select a different weighting method or input their own algorithm.

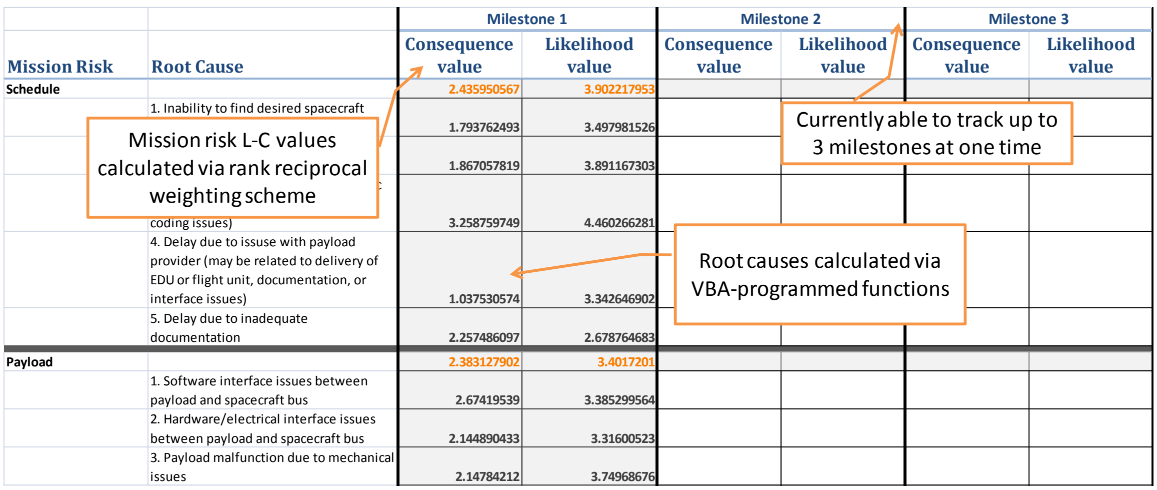


Figure 3.11 - Risk Tool Outputs page

3.5.3 Plots page

The plots page, shown in Figure 3.12, provides a quick and easy way to view the mission risks on a traditional L-C chart. The mission risk consequence is plotted on the x-axis while the likelihood is plotted on the y-axis. Familiarity and ease of use were the primary motivators for the development of this plots page. The mission risk L-C values are copied from the outputs page and displayed next to the 5x5 chart for quick reference. If the user chooses to track multiple milestones, these additional mission risk values are located along the bottom of the 5x5 chart. The color of the milestone value background corresponds with the text boxes on the 5x5 chart. Additionally, interactive macro-enabled buttons allow the user to plot combinations of milestones, combinations of risks, or the ability to mix and match milestones and risks. Furthermore, the diagram is easily copied to presentations for mission status updates.

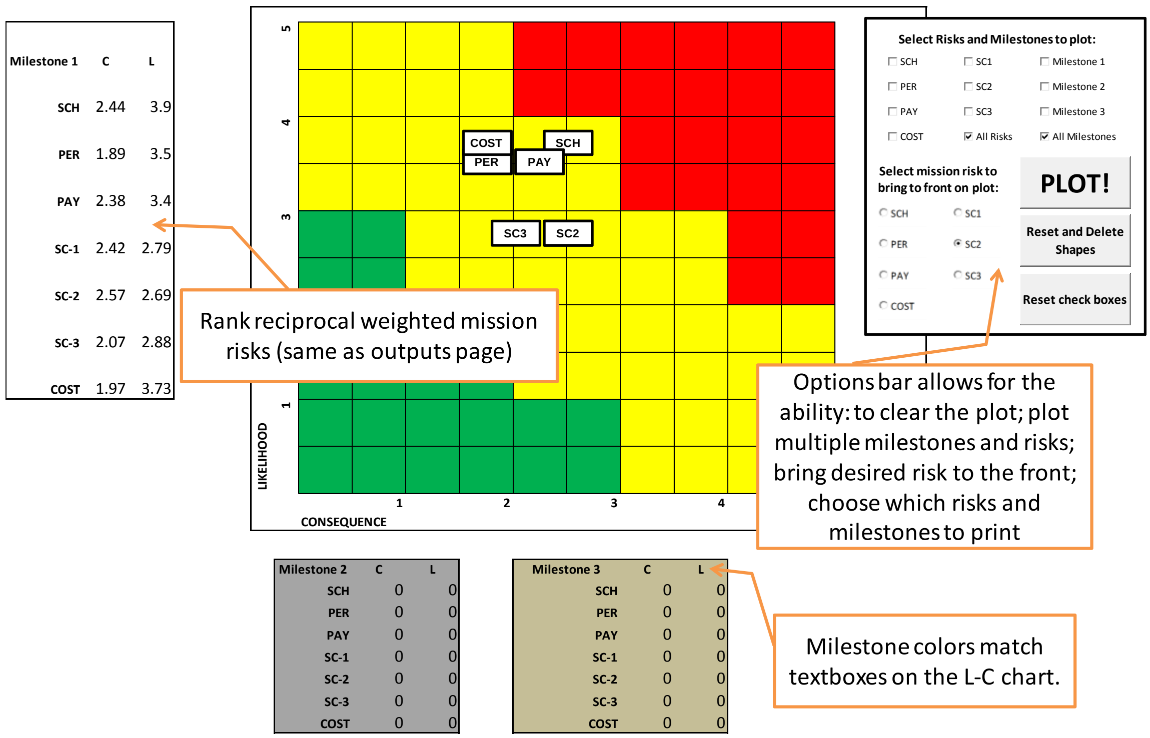


Figure 3.12 - Risk Tool Plots page

This chapter has described the development of the CubeSat Risk Analysis software tool, including gathering the data through the use of a survey, processing of the survey data into the necessary format for regression, the application of General Error Regression to the small satellite data, and the design of the software tool itself. As with any software package prior to its release, the tool must be thoroughly tested and validated, which is the subject of the next chapter.

Chapter Notes

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Chapter 4: Validation of CubeSat Risk Analysis Software Tool

In an effort to determine that the derived risk estimating relationships successfully predict CubeSat mission risk, the Risk Analysis Tool was subjected to a number of different testing and validation methods, including outlier analysis, trade studies, and model validation techniques. According to Snee, there are four types of regression model validation: comparison of model predictions and coefficients with theory, collection of new data to check model predictions, comparison of results with theoretical models and simulated data, and cross-validation.[1] Because no theory exists for risk estimating relationships, it is difficult to complete the first method of validation suggested by Snee other than moving outside the data ranges to test the extrapolation capability of the RERs. The CubeSat Mission Risk Survey described earlier serves as the first-ever collection of data needed for deriving these risk estimating relationships. Thus, no other data readily exists for checking model predictions in the near term. Similar to the first method, no theoretical models or accurate simulated data exist by which to compare the derived relationships. Therefore, the software tool and its risk estimating relationships are first validated by a version of cross-validation followed by testing the extrapolation capability by moving outside the data ranges used to derive the RERs. Stone[2] and Shao[3] both describe methods of cross-validation as using a portion of data on which to base the regression coefficients while reserving the rest of the data for testing the model predictions. After conversations with the developers of the USCM and SSCM models, the best approach was selected as the “Leave-One-Out”, or “simple” cross-validation methodology.

4.1 OUTLIERS

Methods of determining outlier data points include residual analysis, box-and-whisker plots, interquartile range calculations, and various other statistical methods. However, many of these methods require the use of certain types of regression models which inherently make a set of assumptions which are not valid for this research.[4]

Because the methods employed in the development of the Risk Analysis tool involved the General Error Regression (GER) technique, the method of determining which data points were outliers relied on comparing the regression Sum of Squared Deviations (SSD) with and without the potential outlier data point. Recall from Chapter 2 that the SSD is a measure of fit between the regression equation and the data. That is, the lower the SSD, the less deviation between the data points and the regression function. So, if removing a data point significantly improves the SSD, then it is concluded the data point is an outlier and should be removed before running the final regression analysis. Significant improvement was judged to be better than a 50% reduction in the SSD value, based on the number of root causes which had a lower SSD value than the baseline analysis. Recall that the regression is completed by root cause within each mission risk.

The candidates for this outlier analysis were hand-picked based on knowledge of the data set and initial analysis showing trends between the demographic inputs and risk-oriented output values. Because of privacy agreements, none of the three mission names will be provided, but the overview of why the missions were considered outliers will be described. While most form factors were quite small, mission #11 had a large form factor, and was thus immediately an outlier concern. Mission #20 had an unusually low value submitted as the time waiting for launch, and mission #50 had a very small time submitted for operations. All of these missions were then flagged as outliers. Notice that these three missions were the only missions selected as outliers, because of unique answers to the CubeSat Mission Risk Survey questions. It was the goal of this research to use all the data possible in order to best represent the gamut of CubeSat missions. The same data were used for the regression analysis of all mission risk – root cause combinations.

To determine whether or not each mission was an outlier, the regression analysis was run on the data without the mission data point. The new SSD values were then compared to the original baseline SSD values. Table 4.1 shows an example comparison when removing mission #50, the mission with an unusually small operations time. The far right column indicates how many of the root cause SSD values for each of the mission risk likelihood (lrc) or consequence (c) analyses were smaller than the baseline value. The impact of removing the mission data is seen by the total number of root cause SSD values which improved as a direct result of excluding this mission from the regression analysis. In other words, root causes which exhibit a decrease in SSD values from the baseline to the trial case are characterized by negative differences in Table 4.1, and these negative differences represent a better fit to the data, since SSD is a measure of how well the equation represents the data. For the case of removing mission #50, Table 4.1 shows that 85.29% of root causes improved when this mission was excluded from regression analysis. Therefore, it was concluded that mission #50 was an outlier.

Table 4.1 - Example outlier comparison of SSD values.

	% Difference between all data and removing 50							# < 0
	RC1	RC2	RC3	RC4	RC5	RC6	RC7	
sch_c_SSD	-17.10	-0.86	-1.88	-2.41	-0.54			5
sch_lrc_SSD	0.18	-0.35	0.05	-3.89	-0.80			3
pay_c_SSD	0.16	-1.59	-6.83	-1.02				3
pay_lrc_SSD	-0.74	0.02	-3.44	-5.90				3
cost_c_SSD	-0.60	-6.70	-17.72	-1.48				4
cost_lrc_SSD	0.17	-3.04	-2.10	-2.08				3
per_c_SSD	13.01	-1.05	-3.10	-2.87	-1.48			4
per_lrc_SSD	-3.64	-23.88	-4.57	-0.14	-4.82			5
sc1_c_SSD	-0.13	-9.99	-13.19	-0.12	-0.73			5
sc1_lrc_SSD	-1.37	-13.95	-7.51	-2.33	-7.17			5
sc2_c_SSD	-1.30	-2.05	-2.32	0.05	-0.44	-0.89	-2.98	6
sc2_lrc_SSD	-2.49	-12.47	-13.63	-10.94	-3.09	-2.29	-15.17	7
sc3_c_SSD	-1.97	-3.54	0.17	0.13				2
sc3_lrc_SSD	-12.86	-4.80	3.68	-1.10				3
							TOTAL	58
							TOTAL %	85.29%

Similar analyses as the one summarized in Table 4.1 were completed for mission #11 and mission #20 and the overall results are summarized in Table 4.2. For each potential outlier mission, the SSD value was sufficiently decreased indicating that all three missions were outliers. In order to increase the predictive accuracy, all three missions were excluded from the regression analysis, but still included in high-level survey results analysis.

Table 4.2 - All potential outlier mission SSD comparisons.

	Mission RCs improved		
	#11	#50	#20
sch_c_SSD	4	5	2
sch_lrc_SSD	1	3	3
pay_c_SSD	1	3	4
pay_lrc_SSD	4	3	1
cost_c_SSD	1	4	1
cost_lrc_SSD	1	3	3
per_c_SSD	3	4	3
per_lrc_SSD	2	5	4
sc1_c_SSD	3	5	5
sc1_lrc_SSD	3	5	5
sc2_c_SSD	3	6	7
sc2_lrc_SSD	5	7	7
sc3_c_SSD	2	2	1
sc3_lrc_SSD	1	3	3
TOTAL	34	58	49
TOTAL %	50%	85.29%	72.06%

4.2 TRADE STUDIES

Many assumptions were made during the development of the Risk Analysis Tool in order to process the data via the combining experts, life-cycle, and launch choice algorithms described in Chapter 3. Of particular interest in these trade studies were the coefficients and function form of the utility curve used to combine experts, the role values assigned to the experts, the life-cycle factor used in translating actual and predicted life-cycle value to the same scale, and a launch choice to numeric value mapping scheme. A series of alternative values were run through the regression analysis in an effort to determine whether the original baseline assumptions were the most appropriate choices. As with the outlier analysis, the SSD value was used to compare the alternative value output to the original baseline values.

4.2.1 Role Value Trade Study

The previous chapter describes how a user's indicated role on the team was translated into a numerical value. However, Chapter 3 supplied the final numerical mapping scheme arrived at through a trade study of three different alternatives, shown in Table 4.3. Notice that Trial 1 involves switching the PI and PM values; Trial 2 and Trial 3 use a different valuation on the core leaders.

Table 4.3 - Role value trade study trials. (* denotes for each subsystem)

	Weight			
Role	**Baseline**	**Trial 1**	**Trial 2**	**Trial 3**
Principal Investigator	1	0.5	0.15	0.5
Program Manager	0.5	0.1	1	1
Systems Engineer	0.35	0.35	0.5	0.75
Chief Engineer	0.35	0.35	0.5	0.75
Subsystem Lead	0.15	0.15	0.25	0.25
Team member	0.05*	0.05*	0.05*	0.05*

Each alternative set of role values were input, the regression analysis re-run, and the SSD values captured for each risk likelihood and consequence. The new SSD values were then compared against the baseline; the number of root causes having smaller SSD values than the baseline were counted. Additionally, an average percent difference for each risk likelihood or consequence was calculated, the number of these averages less than zero was reported ("TOT Avg < 0"), and an average of all these averages was also calculated ("Avg of Avg").

Table 4.4 - Role value trade study results.

Model	Number of RCs < 0	% RCs < 0	TOT Avg < 0	Avg of Avg
rTrial_1	43	63.235%	9	-0.2977
rTrial_2	42	61.765%	10	-0.6963
rTrial_3	46	67.647%	11	-0.5625

The results of Table 4.4 show that the baseline set of role values may not have been the most appropriate. Instead, the Trial 3 mapping scheme is the most effective, since it has a greater number of root causes which improved from the baseline than Trial 1, and a higher number of averages which improved than Trial 2. Therefore, the role values used in the final development of the software tool, as described in Chapter 3, are the values associated with Trial 3 given in Table 4.3.

4.2.2 Utility Curve Trade Study

After first defining how user-indicated roles on the mission translate to a numerical value, it is necessary to combine the user's role and years of experience to a weight, or a measure of the usefulness of their survey response. For the purposes of combining multiple expert opinions to a single data point for a given mission, it was necessary to determine weights for each expert. It was decided that the weights, or usefulness of the response, were a function of the expert's years of experience and the role on the team. Because an expert could have any combination of these values, a continuous function was deemed the most appropriate. To find this function, the six different functions listed in Table 4.5 and shown graphically in Figure 4.1, with years experience on the horizontal axis, were tested. Note that the baseline function was arbitrarily chosen. These functions were chosen specifically because of the relationship for increasing relevance as experience and role increased. Part of the trade study exploration, though, was to determine how steep this relevance curve should be and whether it should continuously increase. The concept of mapping a set of inputs to the usefulness of the result is part of Utility Theory as described in Chapter 2.

Table 4.5 - Utility curve trade study alternatives

	Function
Baseline	$u(yrs, role) = \log(0.5 * yrs * role + 1)$
Trial 1	$u(yrs, role) = yrs^{\frac{1}{4}} + role^{\frac{1}{6}}$
Trial 2	$u(yrs, role) = \log(yrs^{0.1*role} + 1)$
Trial 3	$u(yrs, role) = 0.05 * (role + yrs)$
Trial 4	$u(yrs, role) = 0.3 * \left(yrs^{\frac{1}{2}} + role^{\frac{1}{3}}\right)$
Trial 5	$u(yrs, role) = (yrs + role)^{\frac{1}{12}}$

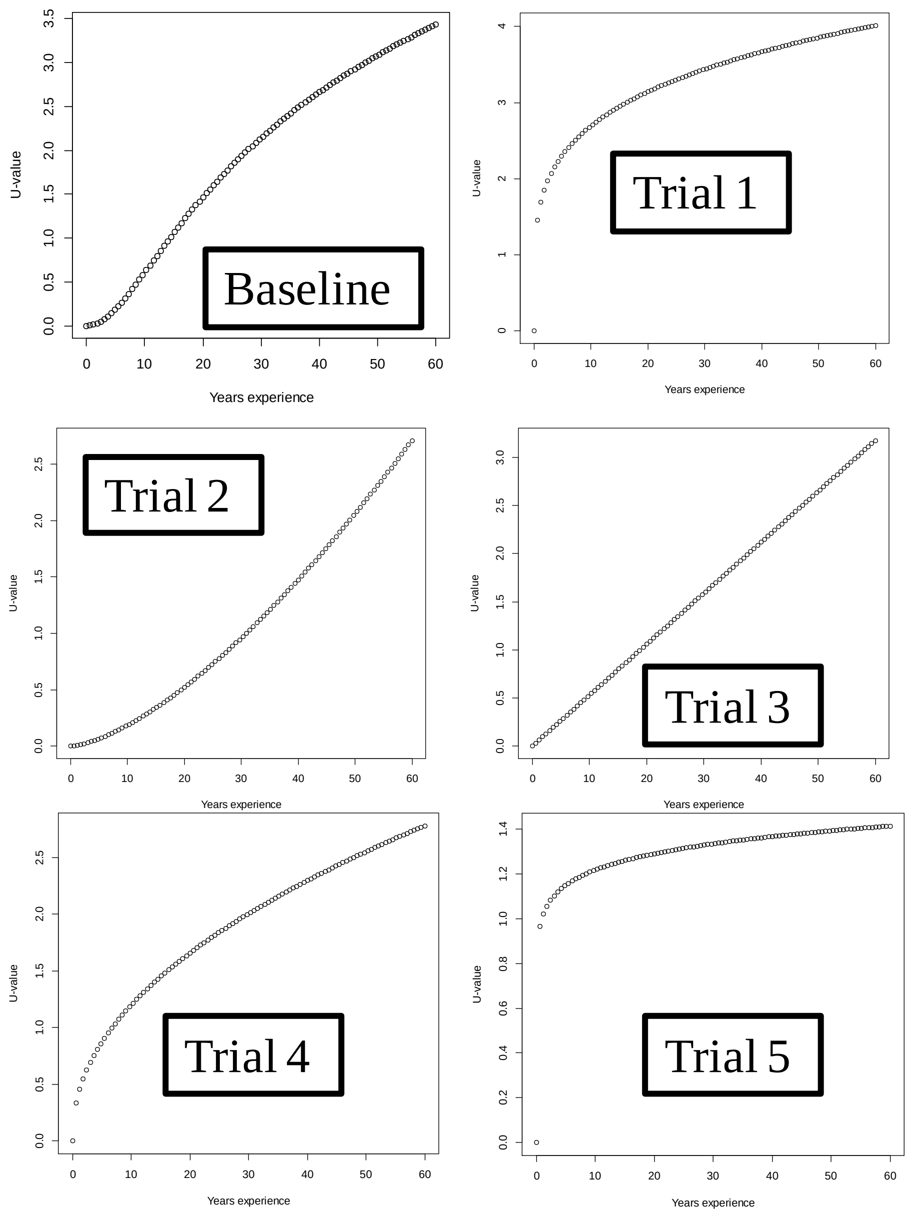

Figure 4.1 - Plots of expert data processing ucurve alternatives.

As with the role value trade study, the different expert response utility curves were used in the data processing algorithms, then the regression analysis was run, and the SSD values for each root cause likelihood and consequence function were compared against the baseline function. Refer to Section 3.4 for an explanation of the regression analysis approach, including how SSD is calculated for each root cause likelihood and consequence function. Table 4.6 shows results in the same format as the Role value results of Table 4.4. Clearly, any choice other than the baseline function would be an improvement in the SSD values. However, notice that Trial 1 has the most number of improved root cause SSD values (51), the greatest improved averages (14), and the highest improved average of all SSD values (-1.44). Therefore, Trial 1 is the utility function referred to in Chapter 3 as the function which maps a user's years of experience and role on the team to their weight used in the combining experts algorithm.

Table 4.6 - Utility curve trade study results.

Model	**Number of RCs < 0**	**% RCs < 0**	**TOT Avg < 0**	**Avg of Avg**
uTrial_1	51	75.000%	14	-1.445
uTrial_2	43	63.235%	12	-0.368
uTrial_3	44	64.706%	10	-0.540
uTrial_4	47	69.118%	12	-0.835
uTrial_5	51	75.000%	11	-1.027

4.2.3 Life-cycle Factor Trade Study

Section 3.3.3 describes the method in which life-cycle estimates are transformed to a common time scale. The equation is repeated here for reference. The common base time (t_{common}) increases as the number of life-cycle steps (j) between the last actual value ($act.last$) and the current predicted value ($t_{predicted}$) increases. Table 4.7 gives an example of how this equation works. If the current life-cycle phase is the "Development" phase and this value is fully known, "actual", then the time prediction holds without any additional factor. When predictions are made, the predicted time is then multiplied by the life-cycle factor coefficient, X, to be studied in this trade study. As the predicted phases move away from the current/actual phase, the coefficient exponentially increases. This trade study focuses on the coefficient value, X = 1.25, and investigates the system response when this value is changed to the alternatives listed in Table 4.8.

$$t_{common} = 1.25^{j-act.last} * t_{predicted} \tag{3.3}$$

Table 4.7 - Life-cycle combination example.

Life-cycle Phase	Development	Integration	Functional Testing
Text	Actual	Predicted	Predicted
Equation	$t_{predicted,1}$	$X * t_{predicted,2}$	$X^2 * t_{predicted,3}$

Table 4.8 - Life-cycle factor trade study alternatives.

	Coefficient value
Baseline	X = 1.25
Trial 1	X = 1
Trial 2	X = 1.5
Trial 3	X = 1.75
Trial 4	X = 2

With the alternatives listed in Table 4.8, the same SSD analysis was completed as in the utility curve and role value trade studies. The life-cycle combination factor trade study results are given in Table 4.9. Notice that none of the alternatives yield a significant, greater than 50%, improvement as was seen in Table 4.4 and Table 4.6 for the role value and utility curve trade studies, respectively. This lack of noteworthy improvement indicates that the baseline life-cycle combination factor was sufficient for the data set collected.

Table 4.9 - Life-cycle trade study results

Model	Number of RCs < 0	% RCs < 0	TOT Avg < 0	Avg of Avg
lcTrial_1	26	38.235%	7	0.365
lcTrial_2	17	25.000%	2	1.728
lcTrial_3	16	23.529%	2	2.207
lcTrial_4	19	27.941%	4	1.912

4.2.4 Launch Choice to Numeric Value Trade Study

When filling out the CubeSat Mission Risk Survey, users were asked to indicate whether they had launched, were manifested, had a promise of a launch through a program such as ELaNa, or no launch information. These textual answers needed to be transformed into numerical values for the regression analysis algorithms explained in Chapter 3. Specifically, the function forms used in the regression analysis, see Table 3.7, refer to the launch choice value as the “launch” variable. It was initially assumed that having more uncertainty (no information on launch) would yield a higher root cause likelihood and consequence value. This is the rationale behind the baseline values for the launch choice numerical mapping trade study alternatives given in Table 4.10.

Table 4.10 - Launch choice numerical mapping alternatives.

	Value			
Response	**Baseline**	**Trial 1**	**Trial 2**	**Trial 3**
No information	4	1	2	1
No, promise	3	2	1.75	1.5
No, manifested	2	3	1.5	1.75
Yes	1	4	1	2

For each launch choice mapping alternative, the regression analysis was run and the SSD values recorded as was done with the role value, utility curve, and life-cycle factor trade studies. Table 4.11 gives the results for the launch choice numerical mapping trade study. None of the alternatives are significantly better than the baseline. Thus, the baseline numerical mapping scheme is what is used in the final regression analysis and software tool.

Table 4.11 - Launch choice numerical mapping trade study results.

Model	**Number of RCs < 0**	**% RCs < 0**	**TOT Avg < 0**	**Avg of Avg**
laTrial_1	1	1.471%	1	0.424
laTrial_2	15	22.059%	7	-0.448
laTrial_3	4	5.882%	2	0.376

4.2.5 Infinite trade study possibilities

The trade studies completed as part of the Risk Analysis Tool validation are but a subset of the possible analyses. There are an infinite number of alternative combinations which could have been studied in the preceding sections, as well as other assumptions which could have been tested. For the purposes of this research, the role value, utility curve, life-cycle factor, and launch indicator were deemed the most critical assumptions to test. In some cases, e.g. role value mapping and utility curve, the baseline assumption was shown to be inadequate and was subsequently updated in the final version of the software tool. On the other hand, the life-cycle factor and launch indicator were shown to be acceptable assumptions and were not modified.

4.3 LEAVE-ONE-OUT / SIMPLE VALIDATION

Stone describes simple cross-validation as the division of the n data into a construction subsample of $(n-1)$ and a validation subsample of size 1. Because of the size of the validation subsample, this technique is referred to as "Leave-One-Out".[2] The construction subsample is used when deriving the coefficients for the function via regression techniques. The function is then tested on its accuracy of prediction with the validation subsample.

This technique was applied to the risk estimating relationships after determining the function form for each of the 68 consequence and likelihood root causes. The simple cross-validation method tests how well the chosen function describes the data when one piece of data is removed the regression calculation. After having used the GER method to obtain the function coefficients with the construction subsample, the purposely missing validation data point was input into the model and values were calculated for each of the 68 root causes. This "Leave-One-Out" process was repeated 49 times for each of the 49 missions under consideration. Recall the sample size was consolidated to 52 missions after processing, and three outliers were removed. Of the 1666 calculated consequence root cause values, 54.5% were calculated to be less than the actual value. Similarly, 57.6% of the likelihood values were calculated to be lower than the actual values. These results indicate that the model shows slight preference for under-prediction.

The model validation techniques described in the literature describe the technique itself, but do not include information on the proof necessary to conclude the model is validated. It is therefore left to the designer to conclude whether or not the validation results meet the expectations of the analysis. The 68 calculated root cause values for each of the 49 missions were compared against the actual values using Equation (4.1). The results are shown in Table 4.12 where 91% of the calculated consequence root causes and nearly 82% of likelihood root cause values fall within +/- 1.5 times the actual value. It is acknowledged that the model is not perfect, and there do exist predicted values beyond these acceptable limits. These outliers are due to the range of values being included in the model construction, especially when removing values as is done with the "Leave-One-Out" method. Section 4.5 will discuss the dangers of moving outside the data range in more detail. The results of Table 4.12 suggest that, for the purposes of the low-cost risk analysis tool, the model is validated, since most of the predicted data matches to within 50% of the actual collected responses.

$$Percent\ Deviation\ = \frac{(actual - calculated)}{actual} x100 \qquad (4.1)$$

Table 4.12 - Percent deviation range for simple cross-validation

Deviation	**Consequence**	**Likelihood**
(+/-) 50%	64.046%	70.648%
(+/-) 100%	80.492%	76.531%
(+/-) 150%	91.116%	81.873%

Note that the survey results are inherently subjective to the opinion and expertise of the respondent. Future iterations of this tool and associated analysis may prove to find better fitting functions. However, for this initial software version, the risk estimating relationships offer an innovative risk analysis tool for CubeSat mission designers.

4.4 ALL-DATA ANALYSIS

In addition to the simple cross-validation technique mentioned in the previous section, high-level analysis was completed to calculate how well the models predicted the values used to derive the function coefficients. That is, all the data were used to derive the coefficients of each function model. Then, each mission was input into the model and the calculated values were compared against the actual values using Equation (4.1). A similar table to Table 4.12 is shown in Table 4.13. Note that only small increases are achieved by using the coefficients derived from all the data in testing the accuracy of the model prediction over the simple cross-validation technique.

Table 4.13 - Percent deviation range of calculated values from actual data

Deviation	Consequence	Likelihood
(+/-) 50%	69.328%	73.830%
(+/-) 100%	82.593%	77.311%
(+/-) 150%	93.337%	82.893%

Because the model validation literature simply provides the technique, but no structured method of accepting or rejecting a model, Table 4.14 and Figure 4.2 provide the information on which this model is validated. Table 4.14 highlights the key measures output by the models: the Sum of Squared Deviations (SSD), Standard Error of Estimate (SEE), and the generalized coefficient of determination (R^2). This table summarizes 34 consequence functions and 34 likelihood function models with the minimized SSD and zero bias values per the MPE-ZPB regression technique described in Chapter 2 while maintaining as small a SEE value as possible. Note that the standard deviation is small for all key statistics, which indicates that there is little variation of SSD, SEE, or R^2 values between the 34 likelihood functions as well as between the 34 consequence functions. The low standard deviation values indicate a majority of the functions have SSD, SEE, and R^2 values near the averages captured in Table 4.14. Recall that the SSD values are a measure of relative error and the SEE values are a measure of percentage error.[5] Thus, it can be concluded that all the functions have similarly small error values. It appears that the R^2 values captured in Table 4.14 are low with what one might expect to find in a regression analysis, and yet the error values are low, which indicates a decent regression fit. It is acknowledged that it may be possible to further decrease the error values and increase the R^2 by using different function forms or methods. However for an initial assessment, the quantities listed in Table 4.14 are deemed appropriate.

As mentioned previously, model validation literature does not provide a concrete method of accepting or rejecting a model, and it was left to the author to determine appropriate criteria. Given the limited number of responses and the preliminary nature of the regression analysis, the author determined the model was validated if a majority of the key statistics data fit within two standard deviations of the average. Figure 4.2 illustrates that all 34 consequence and 34 likelihood root cause SSD, SEE, and R^2 values fit within three standard deviations with most of the values fitting within two standard deviations.

The model is accepted because of its ability to capture the root cause consequence and likelihood values with overall small error and variation. It is acknowledged that the conclusion of successful model validation is subjective. However, for the purposes of the initial risk estimating relationships, the values of Table 4.14 and the root cause distribution of Figure 4.2 indicate success. To improve the model and further reduce the SSD and SEE while increasing the R^2 values, additional function choices could be tested in future iterations of this analysis.

Table 4.14 - Key statistics of function models based on full dataset

	Consequence			**Likelihood**		
	SSD	**SEE**	**R^2**	**SSD**	**SEE**	**R^2**
MAX	4.4064	0.6800	0.3800	4.4663	0.7444	0.3592
AVG	2.8381	0.4586	0.2496	2.8945	0.4723	0.1815
MIN	1.7904	0.2984	0.0874	2.0974	0.3315	0.0009
STDEV	0.5786	0.0884	0.0778	0.5711	0.0917	0.0925

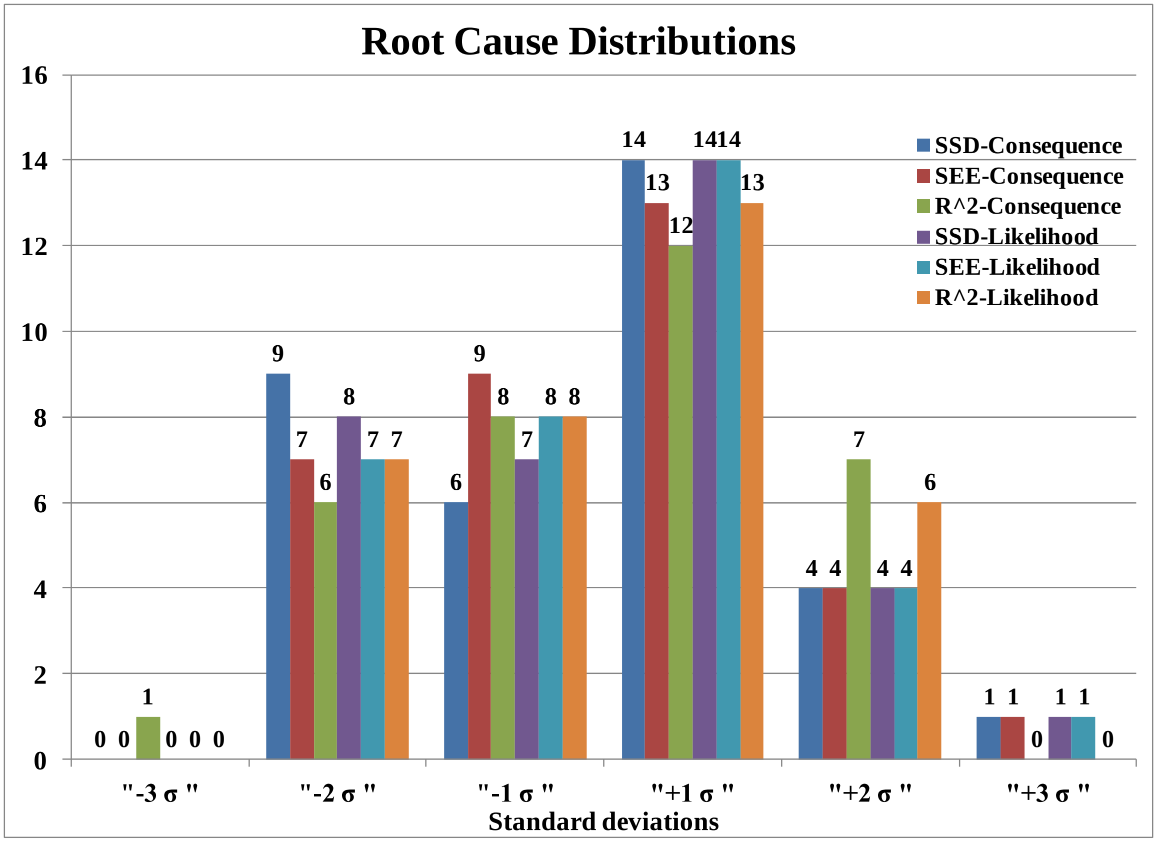

Figure 4.2 - Root cause key value distributions

4.5 STRATIFIED TESTING VALIDATION

Similar to Stone, McCarthy[6] identifies an additional method of validating mathematical models by clustering the data into groups of similar characteristics and sampling from those groups to form the training (construction) and testing (validation) data sets. The training set is then used in the regression while the testing set is used to determine how accurate the model is in predicting the data points. For the purposes of this analysis, the post-processed data were clustered in two ways: by form factor and by launch indicator. These strata were then randomly split in half to obtain the testing and training data.

Unfortunately, when data points are removed from the construction of the RER equations, the accuracy will become worse, as illustrated in Table 4.15. The "Leave-One-Out" section of the table was described in Section 4.3 and the "All-Data" was described in Section 4.4. The "Form Factor" and "Launch Indicator" sections are the result of this stratified cross-validation technique where the data is organized according to the form factor and launch indicator and sampled according to these strata, respectively. Note that the Form Factor and Launch Indicator sections use approximately half the data to build the RER equations and half the data to test the accuracy of the relationships. Thus, the accuracy is worse with the stratified method than when all, or nearly all, of the data is used as in the All-Data and Leave-One-Out trials, respectively.

Table 4.15 - Comparison of model validation methods

Form Factor			**Leave-One-Out**		
Deviation	**C**	**L**	**Deviation**	**C**	**L**
(+/-) 50%	55.882%	61.397%	**(+/-) 50%**	64.046%	70.648%
(+/-) 100%	74.387%	72.672%	**(+/-) 100%**	80.492%	76.531%
(+/-) 150%	83.701%	78.922%	**(+/-) 150%**	91.116%	81.873%
Launch Indicator			**All-Data**		
Deviation	**C**	**L**	**Deviation**	**C**	**L**
(+/-) 50%	59.559%	64.461%	**(+/-) 50%**	69.328%	73.830%
(+/-) 100%	73.529%	73.652%	**(+/-) 100%**	82.593%	77.311%
(+/-) 150%	82.598%	78.922%	**(+/-) 150%**	93.337%	82.893%

The stratified cross-validation technique was used in an effort to try several model validation techniques in order to prove these Risk Estimating Relationships accurate. However, with limited data, it is more prudent to use the results of the Simple Cross-Validation technique and the All-Data Analysis to determine whether or not the model is sufficiently validated. Since the Leave-One-Out and All-Data Analysis trials show predictive accuracy, it is concluded that the equations are effectively validated and may be used by CubeSat mission designers for helping to identify risks affecting their mission success. Potential modification to the algorithm and its resulting improvement by validation are left as work for future research.

4.6 Moving Outside Data Range Validation

Another validation technique proposed by Snee involves testing the regression equations by using data outside the ranges used to construct the model.[1] The risk analysis model used data with the ranges shown in Table 4.16. Here, FF represents the form factor of CubeSat Units, e.g. 1U, 2U, 3U. Launch indicates whether or not the mission has launched, see Table 3.6 for more information. Dev, Int, Func Testing, Environ testing, Waiting, and Ops represent the time (months) in development, integration, spacecraft functional testing, environmental testing, waiting for launch, and operations, respectively. Fourteen trial cases were devised to test the model's predictive capability after increasing and decreasing the input values from the maxima and minima, respectively, shown in Table 4.17. Only one Factor of Interest (FOI) was changed for each trial case, and the remaining FOIs were input as their respective rounded average values in Table 4.16. The fourteen trial cases are shown in Table 4.17. The first seven trials involved increasing the input values while the second seven trials decreased the FOI from the limits below.

Table 4.16 - Model input data ranges

							Life-cycle Duration (Months)			
	FF (U)	**Mass (kg)**	**Launch**	**Year**	**Dev**	**Int**	**Func Testing**	**Environ testing**	**Waiting**	**Ops**
Max	6	15	4	2016	83.60	45.78	23.44	23.44	87.89	73.24
Average	2.62	3.80	2.45	2013	30.17	10.27	6.68	4.95	14.67	21.82
Min	1	0.6	1	2009	5	1	0.878	0.47	1	2.44

Table 4.17 - Trial cases for testing outside data ranges

Case	FOI	FF	Mass	Dev	Int	Func Testing	Environ testing	Waiting	Ops
1	FF	12	15.96	30	10	7	5	15	22
2	Dev	3	4	100	10	7	5	15	22
3	Int	3	4	36	60	7	5	15	22
4	Func testing	3	4	36	10	40	5	15	22
5	Environ testing	3	4	36	10	7	40	15	22
6	Waiting	3	4	36	10	7	5	100	22
7	Ops	3	4	36	10	7	5	15	100
8	FF	0.5	0.665	36	10	7	5	15	22
9	Dev	3	4	1	10	7	5	15	22
10	Int	3	4	36	0.5	7	5	15	22
11	Func testing	3	4	36	10	0.25	5	15	22
12	Environ testing	3	4	36	10	7	0.25	15	22
13	Waiting	3	4	36	10	7	5	0.51	22
14	Ops	3	4	36	10	7	5	15	1

The software tool recognizes when extremely large positive values are calculated, and replaces these values with the maximum range value 5. Similarly, when largely negative values are calculated the software replaces the value with 2.5 to represent the most uncertainty available in the model. Also, when the output value is calculated to be between 0 and -1, the value is replaced with a 0. With these data assurances installed, the trial cases resulted in the plots shown in Figure 4.3. In both the Consequence and Likelihood analyses, Cases 14, 13, and 11 generate largely positive and largely negative values (represented by 5, 2.5). Case 12 generates many largely negative values in Consequence, but largely positive in Likelihood. For Case 9, the biggest impact is largely negative Likelihood values. Cases 1, 3 and 5 have some largely positive Consequence values. Cases 3 and 5 have some largely positive Likelihood values. In general, more cases are likely to produce both largely negative and largely positive Likelihood values due to the nature of the data processing.

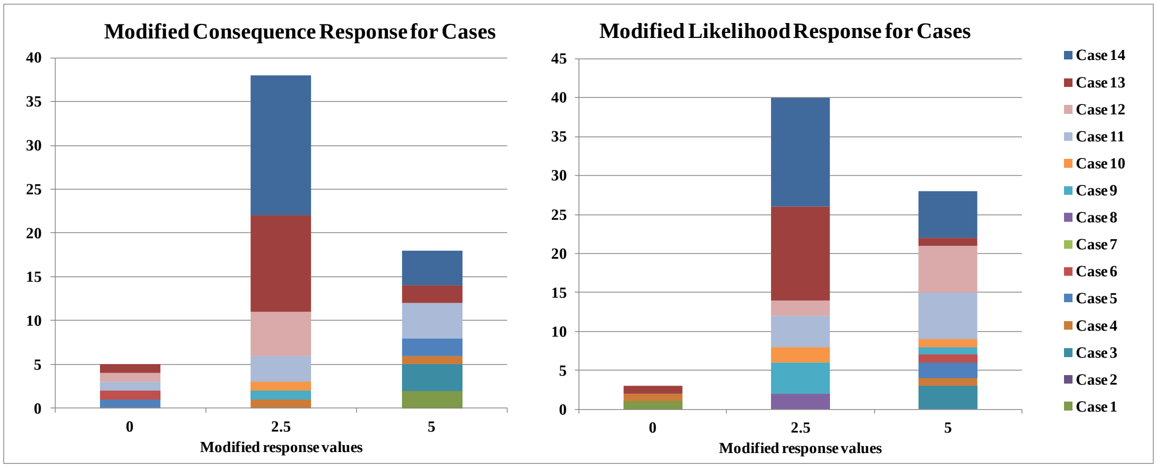

Figure 4.3 - Outside data range response - Consequence (left), Likelihood (right)

This test shows that the risk model is not well equipped to handle drastic decreases in the life-cycle development time inputs beyond the minimum values used in the model construction. This is evidenced by the severe increase of largely negative and largely positive Consequence and Likelihood values for those cases. It should be noted that decreasing the form factor accounts for only two of the largely negative Likelihood values and the rest are due to the life-cycle inputs. Furthermore, only in the largely positive Consequence category (a value of 5) is there any substantive representation of the trial cases involving increasing the FOI values. In other words, the risk estimating relationships are more sensitive to changes in mission life-cycle and less sensitive to changes in satellite form factor.

Moving beyond the ranges of the data used to construct the model is purely meant to educate the users of this software tool of the sensitivities associated with inputting their data. However, if the data is within the expected range, the user may conclude that the risk likelihood and consequence values are good estimates.

4.7 DISCUSSION OF VALIDATION RESULTS

Conversations with model developers as well as analysis of regression validation literature show that there is no concrete method to prove a regression model successfully represents the data of interest. It is therefore left to the analyst to determine appropriate metrics by which to measure their validation results. For the purposes of this software tool, the regression was deemed validated if more than half the data was accurately represented to within +/- 50% of the actual value. This criteria was tested via four different methods, and Table 4.12 through Table 4.15 illustrate that the criteria was met in all cases, even when using the least accurate, stratified, cross-validation approach. Additionally, Table 4.15 shows that all methods of cross-validation produce similar results. That is, no method of cross-validation shows a significant reduction in the model's ability to predict the actual values. Instead, the results are as one would expect. The models which used the most data were best at prediction while the model which used the least data, the stratified approach, was worst at prediction. Because the cross-validation results follow expectation, it is concluded these techniques were executed successfully. Furthermore, since the criteria of at least half of the data being represented to within +/- 50% of the actual value was met, it is concluded that these cross-validation techniques successfully validate the regression models used in the CubeSat Risk Analysis tool.

The results of validation by moving outside the data range illustrate the dangers of a user inputting values which were not used in the formulation of the regression model. It was expected that the model would be able to extrapolate the risk calculations for inputs outside the acceptable data range. The results of Section 4.6 show this intuition to be correct for values larger than the maximum data entry. Interestingly, the tool had the most difficulty with input values smaller than the acceptable data range. This makes physical and logical sense because the input parameters can only be so small, and the minimum values are already at the lower boundary of what is physically possible. Namely, size and time cannot be negative. The model was unable to properly represent these small, but positive, values. One potential way to alleviate this issue would be to obtain data specifically corresponding to small CubeSats (<1U) which also had a rapid development cycle (<1 month in each phase).

4.8 CubeSat Risk Analysis Concluding Remarks

The CubeSat Risk Analysis Tool was released to the CubeSat Community in April 2014. Since then, 71 individuals have requested access to the tool through a short survey which allows demographic tracking of tool users. Figure 4.4 and Figure 4.5 show a summary of the user demographics as of April 2015. The tool was primarily meant for students, and Figure 4.4 illustrates that a majority of the users are, in fact, universities. However, there are a significant number of corporate and government users as well. Interestingly, the majority of requests have come from international universities, which highlights the increasing popularity of the CubeSat platform throughout the world. Many of the users have also indicated that they plan to pass the tool on to other colleagues.

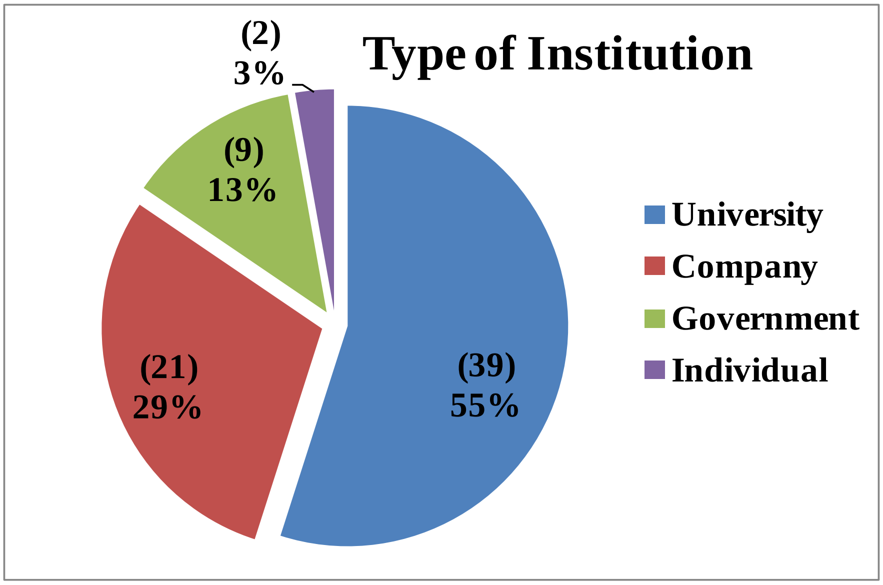

Figure 4.4 - Risk Analysis Tool User Institutions.

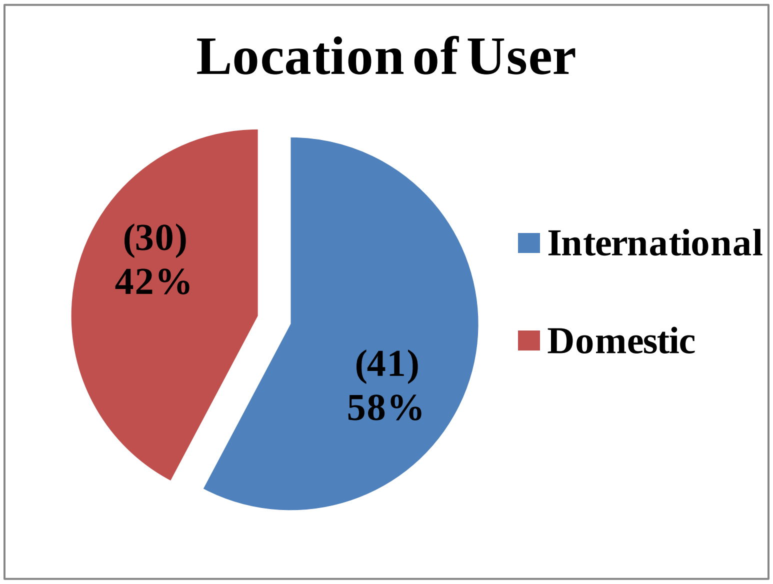

Figure 4.5 - Risk Analysis Tool location of user

Despite many requests for feedback from the users who requested the CubeSat Risk Analysis tool, only three responded with suggestions. Mostly, these recommendations were to include more information on the various elements of the tool as the user was inputting or analyzing their data, e.g. pop-up information blocks to help them better understand the tool. No significant issues were discovered through these users' analyses. One user, in fact, published a study using the CubeSat Risk Analysis tool to compare the risk profiles between multiple missions.[7]

Having shown that the CubeSat Risk Analysis tool is validated and currently being used, the first portion of this research is concluded. The CubeSat Risk Analysis Tool, however, only helps the user identify and quantify the mission risks. The next logical question is "Now what?" The second portion of the research, beginning with the next chapter, strives to answer this question by helping users pinpoint the best methods of mitigating these mission risks based on their own preferences through decision analysis and utility theory.

Chapter Notes:

[1] Snee, R. "Validation of Regression Models: Methods and Examples." *Technometrics* 19 (1977): 415-428. Web.

[2] Stone, M. "Cross-validating choice and assessment of statistical predictions (with discussion)." *Journal of the Royal Statistical Society, Series B* 36 (1974): 111-147. Web.

[3] Shao, J. "Linear Model Selection by Cross-validation." *Journal of the American Statistical Association* 88 (1993): 486-494. Web.

[4] Ben-Gal, I., "Outlier detection." *Data Mining and Knowledge Discovery Handbook: A Complete Guide for Practitioners and Researchers*. Ed. Maimon, O. and Rockach, L. New York: Springer, 2005. Print.

[5] Book, S.A. and Young, P.H. "General-Error Regression for Deriving Cost-Estimating Relationships." *Journal of Cost Analysis* 14 (1997): 1-28. Web.

[6] McCarthy, P. J. "The use of balanced half-sample replication in cross-validation studies." *Journal of the American Statistical Association* 71 (1976): 596-604. Web.

[7] Dal Piaz, M. A. L. et al. "Risk Analysis Comparison Between The Mission NANOSATC-BR1 And NANOSATC-BR2." Congresso Nacional dos Estudantes de Engenharia Mecânica, 6-10 October 2014.

Chapter 5: CubeSat Decision Advisor Software Tool

Once a mission risk is identified and quantified, as with the CubeSat Risk Analysis Tool described in the previous chapters, it is usually the responsibility of the systems engineer to determine the best ways to mitigate the mission risk. Recall the mitigation categories listed in Table 1.1 of avoiding, transferring, controlling, or assuming the risk. But which of these would best suit the mission? How should the mission implement these methods? The CubeSat Decision Advisor Software Tool is the second half of the small satellite risk management software tool suite, and is meant to answer these questions and aid the user in determining how best to mitigate the risks identified while using the CubeSat Risk Analysis Tool.

Chapter 2 described the principles of decision analysis used in the development of the CubeSat Decision Advisor. This chapter specifically describes how these concepts are used in practice throughout the software tool. The tool employs a normative risk management methodology with an interactive framework by which users can examine their spacecraft mission risks. The risk management function of the software tool queries users for their choice of mitigation techniques and the probability of success for each technique, their cost, time, and people resource allocation, and their outcome preferences. Together, these inputs generate the utility curves which are then used for determining the expected utility of each mitigation technique and ultimately for providing the suggestions captured on the Summary page.

5.1 TOOL OVERVIEW

As described in Chapter 1, decision theory has commonly been used in applications of insurance, investment strategy, the oil and gas industry, medicine, and a variety of other industries. Existing applications in the aerospace industry are limited to large-scale missions or design studies. This software tool serves as the first known application of decision theory to the emerging topic of small spacecraft missions. The tool uses the methods of decision analysis applied to the area of spacecraft risk management to identify the mission risk and/or root cause which, when mitigated, is the most efficient use of resources given the user-defined constraints of implementation cost, people needed, and time to completion. The software tool solves this problem via multi-attribute utility theory combined with decision analysis principles and is purposely designed for use by a spacecraft mission designer of any background or experience level. The software prompts the user to enter their mission-specific data, and provides options for the user to select the calculations they wish to analyze.

An initial effort has been made to appropriately scale risk management practices to smaller satellites, since risks associated with larger (500 kg) class missions do not necessarily reflect risks associated with CubeSat missions. Related research identified seven primary mission risks and 32 root causes for these risk events.[1,2] These risks, listed in Table 5.1, and their associated root causes are used as the framework for the CubeSat Decision Advisor software tool.

The CubeSat Decision Advisor software tool contains a number of worksheets, and each serves a different purpose. The Summary page, shown in Figure 5.1, displays all the relevant information needed to make a decision regarding which mitigation technique is the most effective way to decrease the mission risk likelihood and/or consequence given the user's preference system, assessment of success probabilities, and resources required for a given mitigation technique. The Summary page also contains the Options bar, circled in green in Figure 5.1, which allows users to select and enter the relevant information for the analysis they wish to complete.

Table 5.1 - Seven mission risks with descriptions

Mission Risk (Acronym)	Description
Schedule (SCH)	The event of a slip in meeting schedule milestones or deadlines.
Payload (PAY)	The event of failure to gather payload data.
Spacecraft-1 (SC1)	The event of inability to communicate with the spacecraft.
Spacecraft-2 (SC2)	The event of inability to gather health data from spacecraft.
Spacecraft-3 (SC3)	Inability to meet spacecraft standards (i.e. international standards for spacecraft design, development, launch, and operation).
Personnel and Management (PER)	The event of insufficient personnel management.
Cost (COST)	The event of lack or delay of funding.

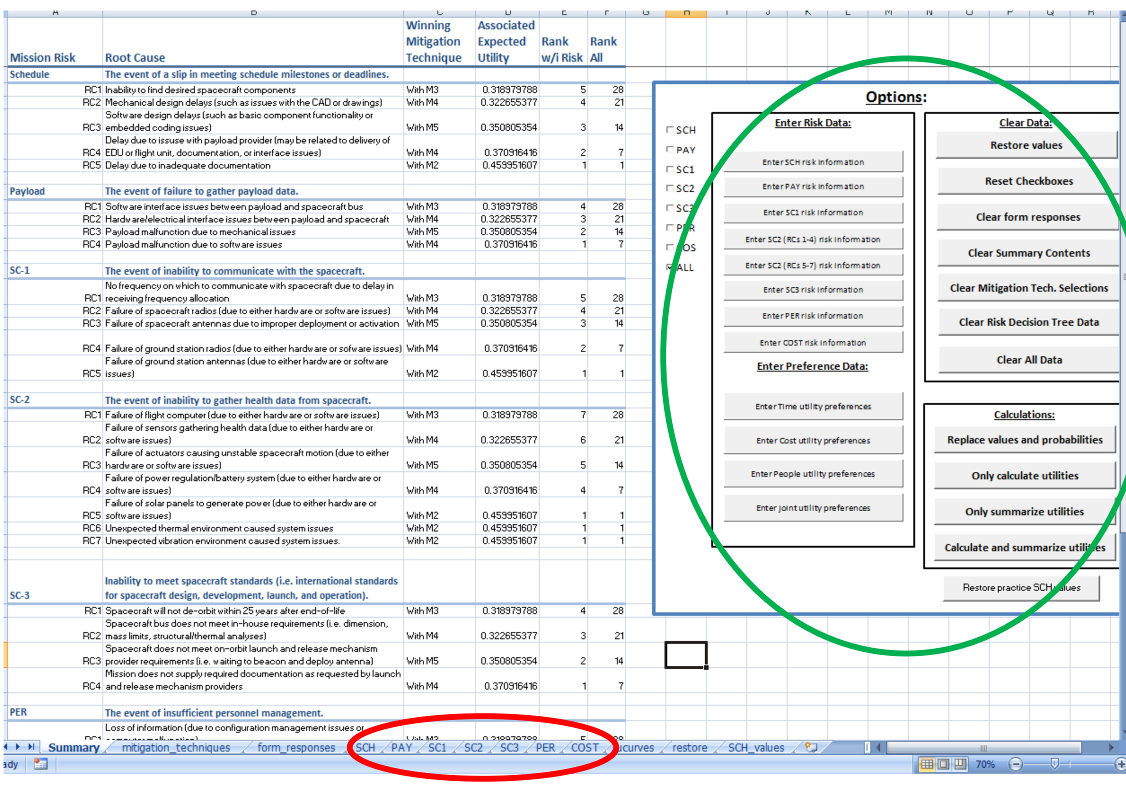

Figure 5.1 - Portion of summary page showing all mission risks

A number of tabs allow the user to inspect and modify various features of the Decision Advisor should they wish to do so. These tabs are circled in red in Figure 5.1. The Mitigation Techniques sheet displays all the possible mitigation techniques for each risk and root cause. This sheet allows users to select a pre-defined mitigation technique, or to write one of their own into the analysis.

Once the user enters information through the Options Bar on the Summary page, the results are captured in the Form Responses sheet. The user will be able to edit this page in the event they realize they entered data incorrectly. The data from the Form Responses sheet is used in the calculations and analysis throughout the tool, therefore it is imperative to ensure the data is correct.

The next seven worksheets in the CubeSat Decision Advisor software tool represent the seven mission risks, as identified during previous portions of this research[1]: Schedule (SCH), Payload (PAY), Spacecraft-1 (SC1), Spacecraft-2 (SC2), Spacecraft-3 (SC3), Personnel and Management (PER), and Cost (COST). Each sheet contains the mission risk decision tree with pre-defined root causes and mitigation techniques to be analyzed. The user-entered data is reflected in the right-most columns of the decision tree – probabilities, implementation cost, people needed, and time estimates. A portion of the Schedule mission risk is shown in Figure 5.2, the other mission risks are similar in format, but will differ based on the user's inputs.

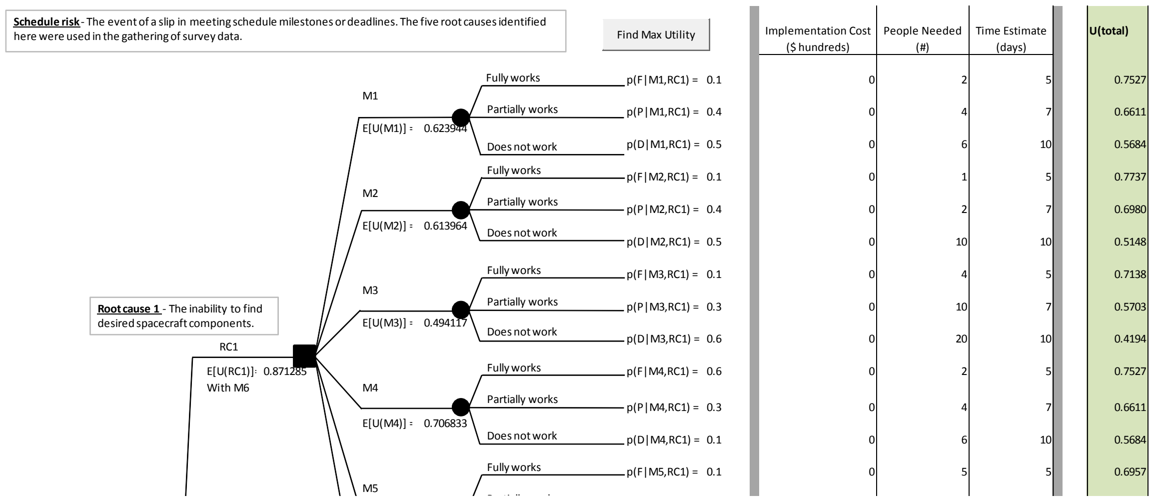

Figure 5.2 - Portion of the schedule (SCH) mission risk decision tree

In addition to the user-accessible pages, there are a few pages which are for internal tool calculations. The ucurves sheet contains the data obtained from eliciting the user's preference system. The restore worksheet stores case study data, so that by the click of a macro-enabled button, the case study data can be restored to the software tool for learning and/or analysis purposes. This is primarily useful for the testing and validation of the tool, so in the event data is lost it can be recovered, but the feature may also help users who simply wish to learn how to use the tool. The Additional ("Addtl") and joint sheets provide analysis for the user-entered data, and will be explained more in Section 5.3.7.

5.2 APPLICATION OF DECISION ANALYSIS THEORY

Decision Analysis and Utility theory was described from a general perspective in Chapter 2. The rest of this chapter describes how these theoretical concepts were practically applied to the problem of small satellite risk management.

5.2.1 Decision Trees and Utility Theory

Figure 5.3 shows how decision theory applies for the problem of small satellite risk management. The seven mission risks, associated root causes, and identified mitigation techniques are represented as decision nodes, since the user faces the decision of which risk and root cause combination to mitigate as well as the technique to implement. The chance node consists of the possibilities that the mitigation technique fully works, partially works, and does not work. The user provides the necessary input data: probabilities, resource allocations, and the choice of mitigation technique through a series of Graphical User Interfaces (GUIs). In addition, the software tool prompts the user for their cost, time, and people value preference systems, to be explained in the next section. After submitting all this data, the user prompts the tool to calculate the expected joint utilities and output the results on the summary page. With the analysis completed by the software tool, the user may then decide which risks or root causes to mitigate.

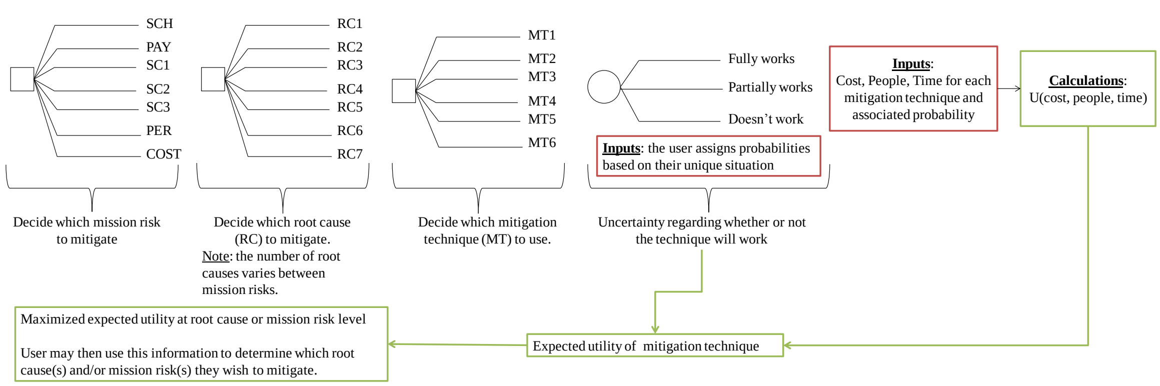

Figure 5.3 - Decision analysis framework

The decision tree is a necessary component of decision analysis. Figure 5.2 shows a portion of the Schedule (SCH) mission risk decision tree. The other six mission risks have a similar decision tree. The root causes are listed in numerical order down the page, each with the associated six mitigation techniques selected for analysis and the three possible outcomes of fully works, partially works, and does not work. When entering the data for each root cause, the user can choose to select up to six mitigation techniques but need not select all six. Any piece of information not provided is assumed to be zero and will not affect the decision analysis. Similarly, if the user deems one of the root causes does not apply to their mission, they need not enter data for that root cause. The input data of cost, people, and time needed for technique implementation are listed to the right of the decision tree, in line with the mitigation technique to which they reference. The joint utility value completes the tree to the right of these input parameters.

Once the user has provided all the necessary input parameter data, they must select the option to replace their data into the decision tree, using the "Replace values and probabilities" option shown in Figure 5.4, which appears in the Options bar of the Summary Page. This button is a Macro-Enabled button and sifts through the data stored in the "form_responses" worksheet, placing the data in the appropriate location of the appropriate risk decision tree. Should the users realize they had incorrectly input data, they are able to update the information in the "form_responses" sheet at any time, and simply click the button again to replace the new data.

After ensuring the data in the risk trees are correct, the user may select "Only calculate utilities" and the software will automatically calculate the expected utility for each mitigation technique of each root cause for all mission risks. The utility functions themselves, as defined in the Utility Theory section, are user-defined functions in Excel VBA. The functions rely upon the user preference system obtained from the Utility Elicitation methods described in the next section. These values fully define not only the utility functions for a given attribute, but the manner in which the single functions are combined to the joint utility function. If "Only summarize utilities" is selected, the software highlights the mitigation technique with the maximum expected utility per each root cause, and places this information in a box at the root cause level of the decision tree as well as on the Summary Page. “Calculate and summarize utilities” first calculates the mitigation technique expected utilities and then summarizes these on the decision tree and on the Summary Page. It is recommended to always use the “Calculate and summarize utilities” option, so as to avoid having calculated the utilities but not having replaced the summary information or vice versa. However, the options exist in separate buttons for tool flexibility. Refer to Section 2.4 for an explanation of expected utility theory.

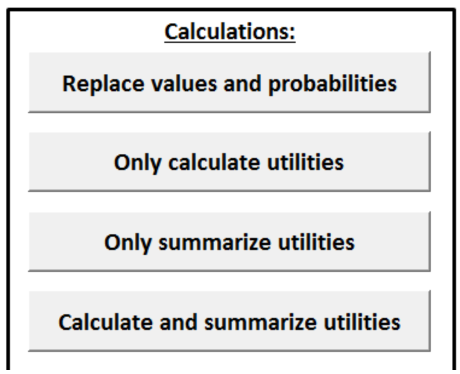

Figure 5.4 - Calculations options on Summary page

Once the utilities have been calculated, and the summaries provided not only on the mission risk worksheets but on the Summary page, the user is ready to make their decision. The Summary page lists all of the mission risks, their root causes, the associated “Winning Mitigation Technique” and expected utility values. In addition, the Summary page lists the rank of that root cause expected utility within the mission risk as well as compared to all root causes. Following the Rules of Actional Thought, as described in Section 2.4.3, the user would choose to mitigate the root cause which has the highest expected utility, with an overall rank of 1. The highest expected utility means that the mitigation technique has the user-defined best combination of success probabilities and cost, people, and time required for implementation. However, it may be possible that the user can afford to implement more than one mitigation technique. The rankings allow the user to successively apply their resources to reduce their mission risk in the most effective manner.

5.2.2 Utility Elicitation

The elicitation of the attribute utility function uses the Preference Comparison Paired-Gamble method presented in Section 2.5 and asks a series of eight lottery comparison questions. The determination of the k_i values exactly follows the Probability Equivalence Standard-Gamble method, and the user is requested to provide a probability that would make them indifferent between the attribute parameter scenarios. This section describes, in detail, the mathematics and programming behind the utility elicitation methods. The Tutorial section offers a quick-start guide to using the software tool, including providing the user with more detailed explanations on entering their preference information via examples.

To enter the attribute utility curve preferences, the user selects one of the following buttons on the Summary page: “Enter Time utility preference”, “Enter Cost utility preference”, or “Enter People utility preference,” as shown in Figure 5.5. Once an option is selected, the associated preference Graphical User Interface (GUI) will appear, such as the one shown for the Cost attribute in Figure 5.6. The first screen for any of the attribute preference GUI screens will prompt the user to enter a maximum value to be used in the analysis. This maximum value identifies the best and worst scenarios. These limiting situations also scale the utility value results so that the best scenarios have a utility value of unity, and the worst situations have a utility of zero. The user must enter a maximum value, otherwise the program will not let them continue. For example, assume the maximum allowable cost to be spent on any mitigation technique is $5000.

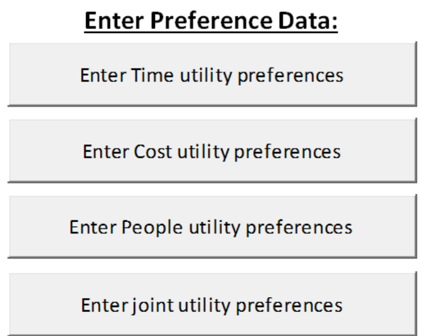

Figure 5.5 - Entering preference data on the summary page

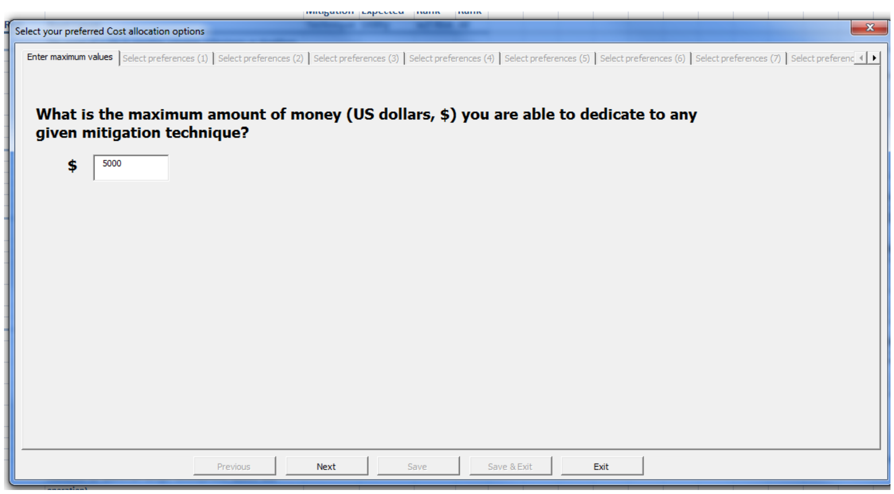

Figure 5.6 - Entering maximum cost allowed

Once the user has entered a maximum attribute value, the following eight screens go through a series of lottery questions with the purpose of teasing out which exponential parameter best describes the user's value preference system. For a description of the utility functions and parameters, see Section 2.5. Each question consists of a set of two lottery scenarios in which the user selects the more preferable scenario. By selecting one lottery over another, one of the utility function forms is selected. When the user finishes the series of eight questions, the tally of utility function selections is calculated and the function with the most scenarios selected is determined to be the user's preference system for the given attribute.

With a maximum allowable cost of $5000, the first lottery scenario is shown in Figure 5.7. This scenario provides two lottery options and asks the user to identify which option more accurately represents their opinion of the cost attribute. The best scenario is defined as a mitigation cost of $0 while the worst case scenario is defined as a cost of the maximum allowable amount. The left-side lottery is asking whether the user thinks $1151 is the certain equivalent of a 10% chance at the best scenario and a 90% chance at the worst scenario. Essentially, if someone were to say, "I guarantee that the mitigation cost will be $1151," would the user find this guarantee equivalent to a 10% chance at the best and a 90% chance at the worst scenarios? Or, as the right-side lottery suggests, does the user value a higher cost, but a higher chance at the best scenario? Is a guarantee of $3497 equivalent to a 25-75 chance at the best and worst scenarios? Most panels of lottery scenarios ask this question: is the user willing to sacrifice a higher chance at the worst scenario for a lower attribute value? If the answer is consistently yes, the user's responses will result in selecting the most conservative utility function. Some of the panels serve as consistency checks in that the questions purposely ask if the user would prefer a lower attribute value for a lower risk value. If the decision-maker is logical, they would consistently prefer the lower value-risk combination.

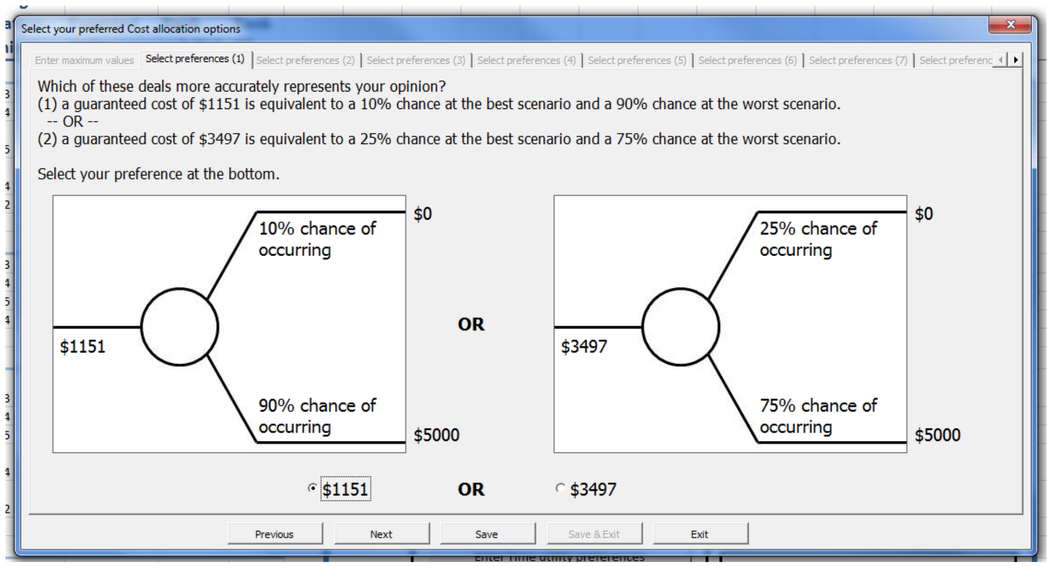

Figure 5.7 - Example lottery scenario for Cost attribute preference

These lottery scenarios are created based on the user's defined maximum value and follow the Continuity Axiom of Table 2.3. Namely, the software is trying to find the certain equivalent that best describes the user's preferences. Recall that the utility functions follow an exponential form, $u(x) = a + be^{-\gamma x}$, with $a = 0$ and $b = 1$. Therefore, changes in utility function are solely due to the change of the gamma parameter. Because the attribute utility functions are scaled according to Equation (5.1), the best and worst scenarios correspond to a utility of 1 and 0, respectively, and the utility of the certain equivalent is then the probability of the lottery. This is because of expected utility calculations: $p * u(best) + (1-p) * u(worst) = p * 1 + (1-p) * 0 = p$. Rather than asking the user to supply a probability or a certain equivalent value, it was decided to provide two lottery options and have the user select the more preferred scenario; each option represents a different γ parameter for the exponential utility function. These certain equivalent options were calculated based on four probabilities, 0.1, 0.25, 0.5, and 0.75. Thus, these four probabilities represent the certain equivalent utility value. The certain equivalent value, *x,* may then be calculated using Equation (5.2) and these values are shown, rounded as in the software, in Table 5.2 for each probability and γ value of an example set of scenarios with specific maximum attribute value amounts: $5000, 10 people, and 20 days.

$$u' = \frac{e^{-\gamma x} - e^{-\gamma x_{max}}}{e^{-\gamma x_{min}} - e^{-\gamma x_{max}}} \tag{5.1}$$

$$x = -\frac{1}{\gamma}\ln(u \cdot (e^{-\gamma x_{min}} - e^{-\gamma x_{max}}) + e^{-\gamma x_{max}}) \tag{5.2}$$

Table 5.2 - Lottery parameters for each attribute and exponential value

	Cost Attribute, $5000 maximum			
p	**γ_1 = 0.01**	**γ_2 = 0.025**	**γ_3 = 0.05**	**γ_4 = 0.1**
0.1	$4,371	$3,499	$2,244	$1,151
0.25	$3,497	$2,332	$1,366	$693
0.5	$2,191	$1,229	$686	$346
0.75	$1,035	$521	$285	$143
	People Attribute, 10 maximum			
p	**γ_1 = 0.05**	**γ_2 = 0.15**	**γ_3 = 0.25**	**γ_4 = 0.5**
0.1	9	8	7	4
0.25	7	6	5	3
0.5	4	3	2	1
0.75	2	1	1	1
	Time Attribute (days), 20 maximum			
p	**γ_1 = 0.01**	**γ_2 = 0.025**	**γ_3 = 0.05**	**γ_4 = 0.1**
0.1	18	17	17	15
0.25	15	14	13	10
0.5	10	9	8	6
0.75	5	4	3	2

The eight scenarios presented on each attribute preference GUI correspond to the same pattern, and represent different combinations of the gamma parameters. The pattern employed for each attribute is shown in Table 5.3. 120 pairs are possible with 16 possible probability-gamma combinations and two combinations per pair, i.e. $C_2^{16} = \binom{16}{2} = 120$. Since the user would not be willing to choose between 120 combinations, it was determined that eight pairs was the proper balance between obtaining enough information and not frustrating the user. These eight combinations are designated by numeric values of 1-8 in Table 5.3. The two cells which have the same number signify the pair which appears on the given number's preference panel of the GUI. For example, the first screen after entering the maximum allowable attribute value is the comparison between a probability of 0.1 and gamma parameter 4 versus a probability of 0.25 and gamma parameter 1. This is evident in the example of a $5000 maximum mitigation cost shown in Figure 5.7. It is observed by means of comparing the parameter combination 1 from Table 5.3 to the values of Table 5.2 that the left-hand lottery corresponds to a gamma parameter of 0.01 while the right-side lottery represents a gamma of 0.05. Recall that Figure 2.3, Figure 2.4, and Figure 2.5 show the utility values for each the Cost, People, and Time attributes, respectively, according to the gamma parameters.

Table 5.3 - Lottery gamma parameter pattern

p	γ_1	γ_2	γ_3	γ_4
0.1				1, 5
0.25	1	5	2, 7	3
0.5	3	2, 4	6	8
0.75	6, 8	7	4	

Once the user completes the set of eight lottery scenarios for a given attribute, the software tallies how many times each gamma parameter was selected and stores this information on a worksheet of the tool. Another Excel VBA routine then determines which gamma parameter was selected the most frequently. In the event of a tie, the more conservative parameter is selected. This most conservative parameter is also selected by default should errors occur during user entry of preferences. The most conservative parameter is defined as the parameter which has the most significant decrease of utility as the value parameters increase. It is observed from Figure 2.3 - Figure 2.5 that this most conservative value also corresponds to the largest gamma parameter, which is evident because the gamma value determines the rate of decay in a decaying exponential function form.

After submitting the preferences for each of the attributes to obtain three attribute utility functions, the user must supply their preferences for the combination of these attribute functions into the joint utility curve. Figure 5.5 shows the option, “Enter joint utility preferences” from which the user can identify their preferences of the combined attributes. This step is crucial for obtaining the parameters necessary to combine the attribute utility functions, the k_i values, per the method discussed in Chapter 2.

After selecting the “Enter joint utility preferences” option, the user will see the screen given in Figure 5.8. This lottery uses the Probability Equivalence Standard-Gamble method and asks the user to supply a probability, p, which would make them indifferent between receiving a specified guaranteed outcome and a p probability chance at the best scenario with a $(1-p)$ chance at the worst scenario. There are only three panels for eliciting the joint utility preferences, as the resulting three values fully characterize the manner in which to combine the attribute utility functions into a joint function.

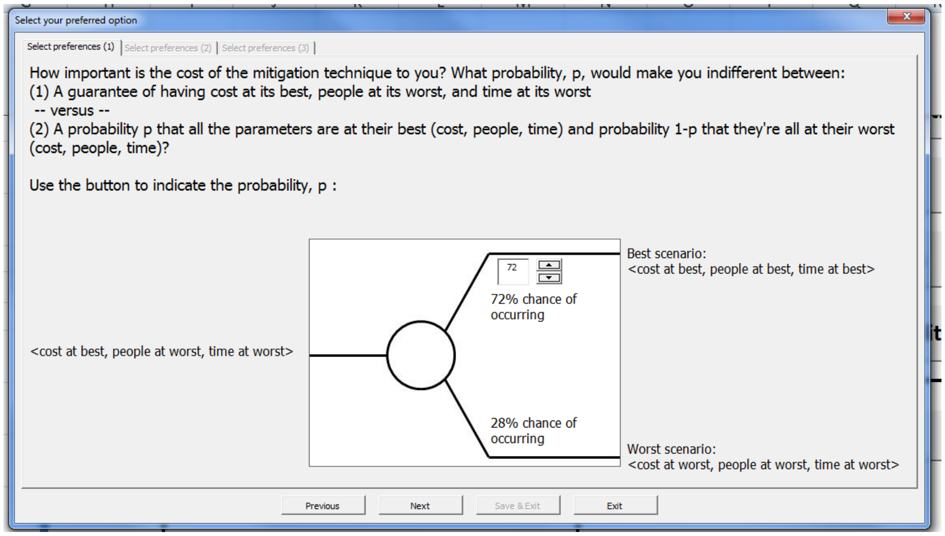

Figure 5.8 - Entering joint utility preferences

The first panel shows a guaranteed outcome of cost at its best, people at its worst, and time at its worst. This combination is denoted by <cost at best, people at worst, time at worst>. Let the lottery of this first panel be denoted as L_1 and represent a chance with p_1 probability that all the attributes are at their best with a $(1 - p_1)$ probability the attributes are at their worst. Recall that the best scenario consists of \$0, 0 people, and 0 days to implement the mitigation technique, whereas the worst scenario consists of the maximum allowable values of each of the attributes. The user is asked to specify what probability p_1 would make them indifferent between the lottery L_1 and a guaranteed set of attribute values consisting of the best cost, \$0, but the maximum number of people and time required for the mitigation technique implementation. Basically, the user is asked for the percentage of the "perfect" case they view the <cost at best, people at worst, time at worst> scenario.

The second panel displays a similar choice to the first panel, only the guaranteed outcome has changed to <cost at worst, people at best, time at worst>. The same lottery exists, and the user is asked to provide another probability value. Namely, the user should indicate the probability p_2 that makes them indifferent between the guaranteed outcome and the lottery, L_2, of a p_2 probability of the best scenario and a $(1 - p_2)$ chance at the worst outcome. With this lottery, the user is determining how highly they value the people attribute when the others are held at their worst values. How much of the "perfect" outcome is the best people attribute value worth by itself?

The third and final panel once again asks the user to provide a probability p_3 which makes them indifferent between the lottery L_3 and the guaranteed outcome of <cost at worst, people at worst, time at best>. Similar to the other two cases, this question is determining the user's value on time. How much of the "perfect" outcome is the best implementation time value worth by itself?

These three panels are asking the user to decide which, if any, of the attributes they value more highly. It is possible to have all attributes viewed equally, in which case the probability values would be the same for each of the three panel scenarios. However, it is possible that users will value one or more of the attributes higher than the others. As an example, assume the user valued cost more highly than the people or time required to complete the mitigation technique, but viewed time and people as equally valuable. The responses for each of the panels in this case could be: $p_1 = 0.9,\ p_2 = 0.7,\ p_3 = 0.7$. A probability value of 0.9 for cost at its best signifies that the user believes this scenario is 90% of the best case possible. Similarly, people, p_2 , and time, p_3, at their best are 70% of the best scenario. If the user did not value one of the attributes, say people, highly, the probabilities could be: $p_1 = 0.9,\ p_2 = 0.2,\ p_3 = 0.7$. This would indicate that people at its best value is only 20% of the best scenario while the cost and time attributes at their best are 90% and 70% of the best outcome, respectively.

The probability values obtained through the three joint utility elicitation panels are equivalent to the k_i values necessary for combining the attribute utility functions into a joint utility function. That is, $p_1 = k_1,\ p_2 = k_2,\ p_3 = k_3$. This is because of the special way in which the questions are asked: two of the three attributes being set to their worst value while one attribute is at its best. With these k_i values, the k value needed to properly combine the attribute utility functions into the joint function according to Equation (2.5) can be found implicitly by an Excel Solver routine following Equation (5.3). Once the user submits their joint attribute probability values via the GUI, these k_i values are stored, and the software tool automatically calculates the k value required to satisfy Equation (5.3).

$$1 + k = (1 + kk_1)(1 + kk_2)(1 + kk_3) \tag{5.3}$$

With the attribute utility functions and k_i values properly defined, the software tool is able to calculate the joint utility value (u-value) for any combination of cost, people, and time inputs. The resulting u-value is then scaled by the best and worst scenarios following Equation (5.4), where u' is the post-scaled u-value and u is the pre-scaled value; the worst case scenario is represented by $u(0,0,0)$ and the best outcome is denoted $u(1,1,1)$. It is these scaled u-values which are used in the decision tree analysis.

$$u' = \frac{u - u(0,0,0)}{u(1,1,1) - u(0,0,0)} \tag{5.4}$$

5.3 TUTORIAL EXAMPLE

The following sequence of steps will guide the user through an example of inputting all the data necessary in order to use the CubeSat Decision Advisor software tool. Detailed descriptions of the decision analysis theory used in the software development can be found in Chapter 2. For specific information on the software development or algorithms, see Section 5.2.

The software tool is a Macro-Enabled Excel workbook and was built in Excel 2007. For the most successful use of the tool, Excel 2007 or newer is recommended. If using an older version of Excel, some functionality may be lost. Additionally, please make sure to enable the Macros and a Solver connection prior to opening the software tool.

5.3.1 Step 0: Open the spreadsheet

To begin using the CubeSat Decision Advisor, first open the spreadsheet "decision_advisor_vX.Y" from which ever location it is currently stored. Note that the X and Y should represent the most current version of the tool. For example, at the time of writing this Tutorial, the software tool was version 1.0. Once the spreadsheet is open, ensure that the Summary page is the current worksheet. If it is not, simply click on the "Summary" tab along the bottom of the screen. Once the Summary page is the active worksheet, the screen should resemble Figure 5.9.

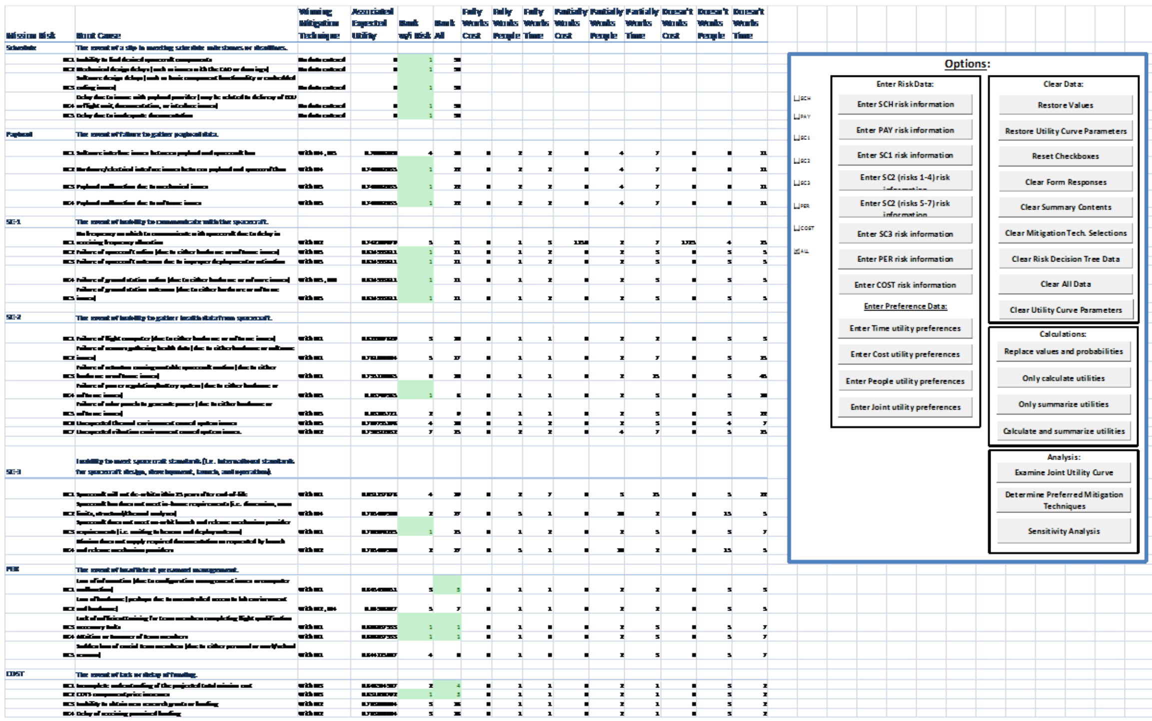

Figure 5.9 - Getting started on the Summary page

5.3.2 Step 1: Ensure mitigation techniques properly encompass mission

In Step 2, the user will select the mitigation techniques they wish to analyze through the decision tree. However, the user should first ensure that the software tool is using the mitigation techniques they would like to study. The Mitigation Techniques worksheet lists all the mitigation techniques for a given mission risk. If the list of mitigation techniques is not sufficient, the user may enter up to three additional mitigation techniques per mission risk in the cells which contain phrases such as "Enter your own mitigation technique #1" , as illustrated in Figure 5.10. Once the user replaces these cells with their own mitigation techniques, the resulting technique will appear as an option in the GUI for the given mission risk, as described in the next step. Note that this worksheet allows the user to keep track of the different types of mitigation techniques: Avoidance, Control, Assumption, and Transfer.[3]

	RC1	RC2	RC3	RC4	RC5	RC6	RC7	Mitigation techniques	Avoid	Control	Assume	Transfer
Schedule	M1	M1	M1	M1	M1	x	x	formulate schedule milestones with students in mind		x		
	M2	M2	M2	M2	M2	x	x	coordinate between sub-groups/subsystems to ensure each group has necessary information		x		
	M3	M3	M3	M3	M3	x	x	work with payload providers to develop payload schedule and deadlines				x
	M4	M4	M4	M4	M4	x	x	build margin into schedule milestones		x		
	M5	M5	M5	M5	M5	x	x	maintain updated documentation throughout mission life cycle			x	
	M6	M6	M6	M6	M6	x	x	allocate more resources to the task needing completion		x		
						x	x	*Enter your own mitigation technique #1*				
						x	x	*Enter your own mitigation technique #2*				
						x	x	*Enter your own mitigation technique #3*				

Figure 5.10 - Mitigation techniques worksheet

5.3.3 Step 2: Enter risk and mitigation technique data

For the decision analysis to apply to a user's mission, they must first enter their unique mission parameters for analysis. The Options Bar on the Summary page contains buttons for entering data relevant to each of the seven mission risks, as shown in Figure 5.11. Note that the Spacecraft-2 risk has two separate buttons; this is due to the limitations of building graphical user interfaces (GUIs) in Excel. If all root causes for the Spacecraft-2 risk are to be analyzed, it is necessary to complete the information on both GUIs. Once a risk button is selected, a GUI, such as the one shown in Figure 5.12, will appear. The user selects the mitigation techniques they wish to analyze, and provides their estimates of success probabilities and resource allocation of cost, time, and people required for each success outcome of each mitigation technique.

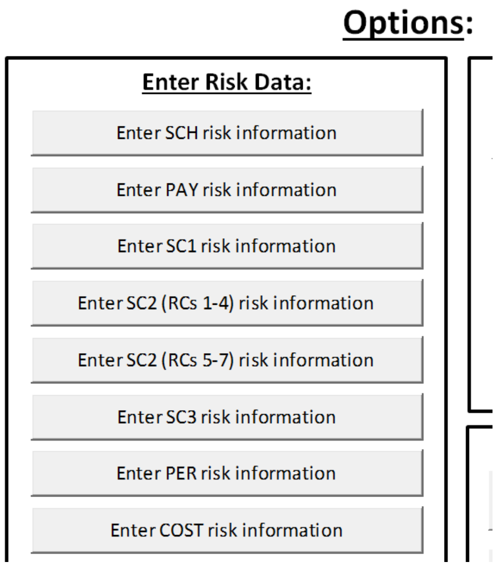

Figure 5.11 - Entering risk data from the Summary page

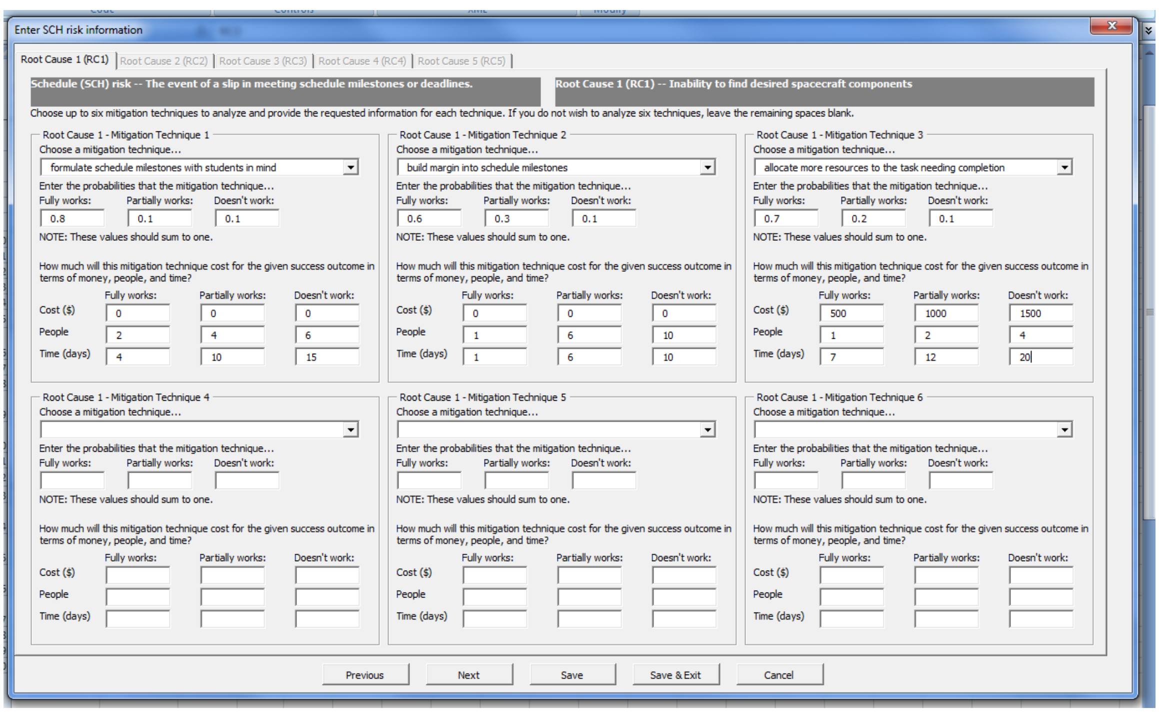

Figure 5.12 - Mission parameter input graphical user interface

The user may choose up to six mitigation techniques to analyze, though they need not select all six. Any single mitigation technique or set of techniques for a root cause left blank will simply be represented by zeros in the analysis and will not affect the results of the other mitigation techniques. It is suggested that the user fill in the desired number of mitigation techniques for each root cause. However, as with the mitigation technique information, any information left blank on a root cause form will not affect the analysis of the other root causes. In other words, if the user desires to analyze the mitigation techniques for only one root cause, they are free to do so. The tool was built with versatility in mind, and allows the users to tailor the analysis to the needs of their mission.

Versatility is also offered in the entry of attribute parameters. Separate boxes exist for three types of mitigation technique outcome: the technique fully works, partially works, and does not work. Users may enter different values into each box to reflect the differences in cost, people, or time required should a technique fully work, only partially work, or not work at all. For example, if a technique fully works, one might expect less cost, people, and time to implement said technique. However, if a technique does not work, one may expect more money, people, and time to be required in order to find the problem with the technique.

The buttons at the bottom of the form allow users to move from one root cause to another, by selecting the “Next” or “Previous” buttons, and to save and/or exit the form. If probabilities are entered, then the tool requires these values sum to one before moving to the next root cause, saving, or exiting the form. If the data is saved, it is stored on the Form Responses sheet. Should the user realize they mistakenly entered incorrect data they are free to modify their responses on the Form Responses sheet. The values on the Form Responses sheet are used in the decision tree calculations.

As an example, assume the user wanted to study three mitigation techniques for the Schedule risk root cause 1 – “Inability to find desired spacecraft components”. Three choices of mitigation techniques and their associated input parameters are given in Table 5.4 and are shown entered into the GUI of Figure 5.12. Having entered the desired data, the “Save & Exit” button is selected resulting in the Form Responses worksheet storing the entered data, as illustrated in Figure 5.13. Notice that there are zeros above and below the entered data, this is because risk information was only entered for three of six mitigation techniques on the second root cause panel.

Table 5.4 - An example of entering risk information

Mitigation Technique 1	*Formulate schedule milestones with students in mind.*		
	Fully Works	**Partially Works**	**Doesn’t Work**
Probability	*0.8*	*0.1*	*0.1*
Cost ($)	*0*	*0*	*0*
People	*2*	*4*	*6*
Time (days)	*4*	*10*	*15*
Mitigation Technique 2	*Build margin into schedule milestones*		
	Fully Works	**Partially Works**	**Doesn’t Work**
Probability	*0.6*	*0.3*	*0.1*
Cost ($)	*0*	*0*	*0*
People	*1*	*6*	*10*
Time (days)	*1*	*6*	*10*
Mitigation Technique 3	*Allocate more resources to the task needing completion*		
	Fully Works	**Partially Works**	**Doesn’t Work**
Probability	*0.7*	*0.2*	*0.1*
Cost ($)	*500*	*1000*	*1500*
People	*1*	*2*	*4*
Time (days)	*7*	*12*	*20*

Risk	Root Cause	MT #	MT Choice	Mitigation Technique	Fully Works Prob	Partially Works Prob	Doesn't Work
SCH	1	1	1	formulate schedule milestones with students in mind	0.8	0.1	0.1
SCH	1	2	4	build margin into schedule milestones	0.6	0.3	0.1
SCH	1	3	6	allocate more resources to the task needing completion	0.7	0.2	0.1
SCH	1	4	0				

Figure 5.13 - Example Form Responses sheet after entry of data

5.3.4 Step 3: Enter outcome preference data

After entering the mission-specific information for analysis, the user must supply their outcome preferences in two manners. First, attribute utility functions are determined for each of the three variables: Time, Cost, and People required for implementation of the mitigation technique. To provide the necessary information for each attribute utility function, simply select the parameter in the Option bar section shown in Figure 5.14. For example, to submit information regarding the time attribute, select the "Enter Time utility preferences" button. Second, the user must supply their evaluations of the relative importance of these three parameters by selecting the "Enter joint utility preferences" button in the Options bar of the Summary page.

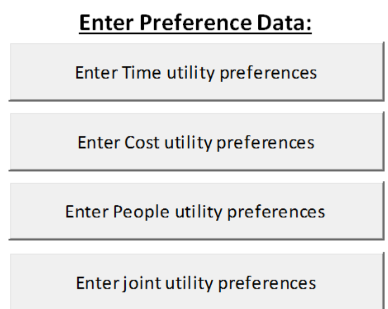

Figure 5.14 - Entering preference data on the Summary page

If the user chooses "Enter Time utility preference," they will first need to enter the maximum number of days they are willing to dedicate to implementing a mitigation technique. This screen is shown in Figure 5.15. This maximum number of days is used to calibrate the remaining responses, and to serve as the worst case scenario.

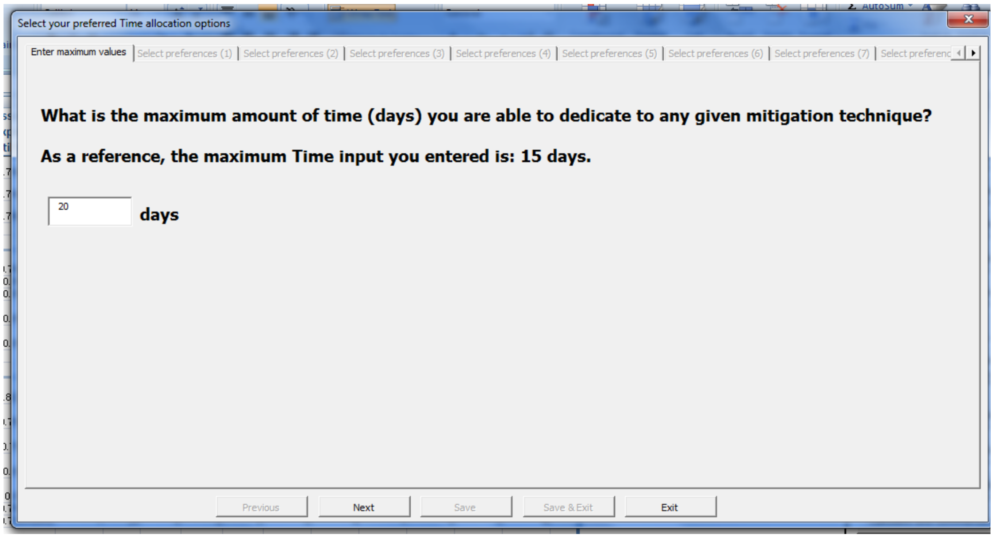

Figure 5.15 - Entering maximum time allowed

For example, let the maximum time allowed be 20 days, as entered in Figure 5.15, the next screen which appears is shown in Figure 5.16. Here, the user decides between two alternatives which help to determine which utility function best represents the user's value system for time. There are a series of eight questions such as the one shown in Figure 5.16. At the end of the eight scenarios, the user's attribute utility curve for the time attribute is established and can be combined with the other parameters once they are determined to form the joint utility function. For a more detailed explanation of the theory behind multi-attribute utility theory, see Chapter 2 and Section 5.2.2.

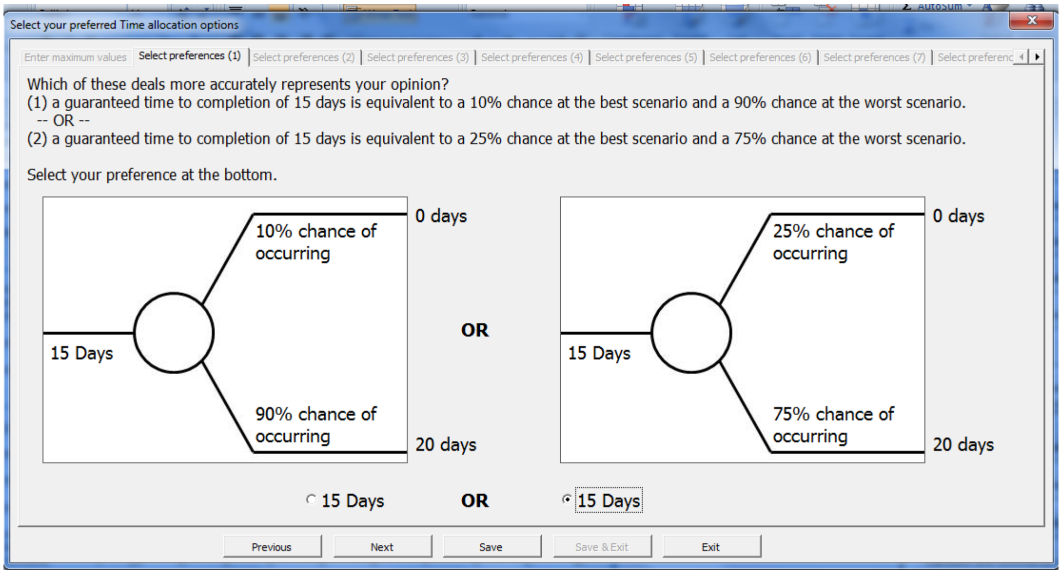

Figure 5.16 - Selecting time preference alternatives

Each scenario of the eight panels is asking the user which lottery system better describes their preference system. The software is asking the user to identify whether or not the certain equivalent meets their preference system. Using the first panel as an example, which scenario better represents the user's preference system: (a) a guaranteed implementation time of 15 days is equivalent to a 10% chance at the best scenario, and a 90% chance at the worst scenario, or (b) 15 days is equivalent to a 25-75 chance at either the best or worst scenarios? In this case, the two implementation times are the same but the chance at the best scenario is different. A rational user would choose (b) because of the higher likelihood of the best outcome.

As an example of completing the Time Preference GUI, assume the user prefers the following scenarios, in order they are displayed:

1. The implementation time is the same, therefore the user prefers the higher chance at the best outcome – "15 days" and "25% chance for 0 days" is chosen.

2. A decrease of 4 days implementation time and a higher chance at the best scenario – “9 days” is chosen.
3. The implementation time is the same, therefore the user prefers the higher chance at the best outcome – “10 days” and “50% chance for 0 days” is chosen.
4. A decrease of 6 days implementation time and a higher chance at the best scenario – “3 days” is chosen.
5. A decrease of 1 day implementation time and a higher chance at the best scenario – “14 days” is chosen.
6. Fewer days implementation time is equivalent to a higher likelihood of the best scenario – “5 days” is chosen.
7. A decrease of 9 day implementation time and a higher chance at the best scenario – “4 days” is chosen.
8. A decrease of 1 day implementation time and a higher chance at the best scenario – “5 days” is chosen.

Once the user identifies their preferences, they are requested to select “Save & Exit”, though they can save their preferences at any time by selecting “Save”. The number of times the user selected certain scenarios is tallied, and their utility function is established per the algorithms described in Section 5.2.2.

Similar to the input of time preferences, the user must enter their cost and people preferences through the Options bar buttons shown in Figure 5.14 by selecting either “Enter Cost utility preferences” and “Enter People utility preferences”. The first screen once the button has been selected will request the user to input the maximum amount of money or people they are willing to use for a given mitigation technique implementation. Then, similar questions to the scenario of Figure 5.16 will determine the user’s attribute utility functions for the cost and people attributes. For this tutorial example, a maximum cost of $5000 and a maximum number of 10 people were assumed. Answers were supplied to similar questions as given in Figure 5.16 so that the cost and people gamma values were determined to be 0.002 and 0.5, respectively.

After each attribute utility function has been entered, the user should select the "Enter joint utility preferences" option shown in Figure 5.14 to provide the information necessary to combine the attribute utility functions into a joint function, as explained in Section 5.2.2. The first screen visible is given in Figure 5.17. The software is asking the user to identify the worth of the cost attribute being at its best value while the people and time attributes are at their maximum, or worst, values. This scenario is denoted by <cost at best, people at worst, time at worst>. The example given in Figure 5.17 shows a user believing that the cost attribute, alone, at its best is worth 72% of the best scenario. In other words, given a choice between the worst scenario and <cost at best, people at worst, time at worst>, the user would choose the latter 72% of the time.

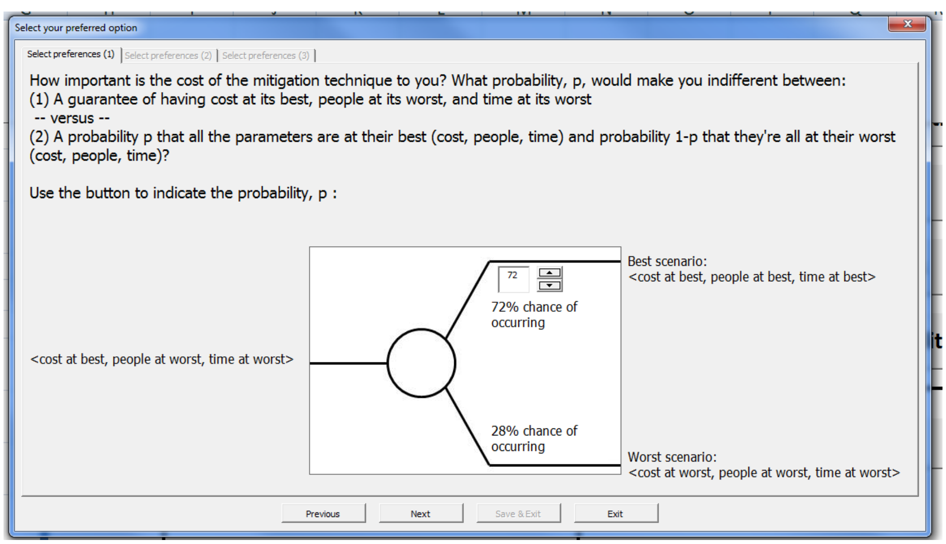

Figure 5.17 - Entering joint utility preferences

Similarly, the second screen contains the same lottery as Figure 5.17, but asks with respect to the combination of cost at its worst, people at its best, and time at its worst. Assume, as example, the user views this scenario as less valuable than the first scenario, and claims it is 60% of the best outcome. The third, and final, screen completes the session with the combination of cost at its worst, people at its worst, and time at its best. Consider a mission under a tremendous time crunch, and the implementation time is highly valuable. In this situation, the user may enter a high value, such as 90%, to indicate this preference. Once the user has supplied these three probability values, they should select "Save & Exit" to complete the process. These three combinations help to establish the values which will allow combination of the attribute utility functions into a joint function.

The joint utility function is what is used during the decision tree calculations to obtain the expected utility for a given mitigation technique. A joint utility function is used to represent the trade space between mitigation techniques with varying costs, people required, and times to completion. Each decision-maker will have a different preference system and may value these three parameters differently than someone else. For a more detailed explanation of these concepts, see Section 2.4 for more information on utility theory.

5.3.5 Step 4: Calculate and Summarize Utilities

Having completed Steps 0-3, the user has entered all the critical information necessary for the software tool to complete its decision analysis calculations. Before running any calculations, however, the user should select the "Replace values and probabilities" option of the Calculations box shown in Figure 5.18. This Excel Macro takes the data obtained from the user's entry of risk information in Step 5.3.3 and places the data in the proper locations of the mission risk decision trees. Should the user realize data is incorrect, they are able to modify the data in the Form Responses worksheet and select the "Replace" option again. Additionally, the choices of mitigation techniques made by the user are captured on the Mitigation Techniques worksheet for future reference during the course of decision-making.

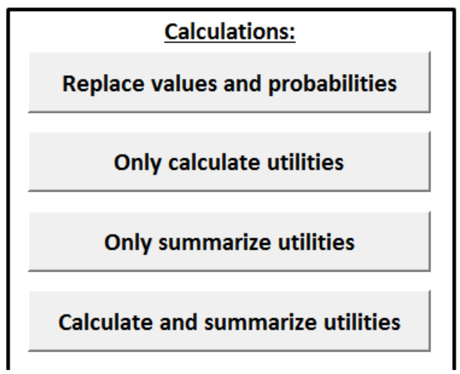

Figure 5.18 - Calculations options

After ensuring the replaced data is correct, the user selects which mission risks they wish to analyze by selecting or de-selecting the checkboxes on the left-hand side of the Options bar, illustrated in Figure 5.19. Recall that these checkboxes represent the seven mission risks, described in Table 5.1, Schedule (SCH), Payload (PAY), Spacecraft-1 (SC1), Spacecraft-2 (SC2), Spacecraft-3 (SC3), Personnel (PER), and Cost (COST). After doing so, the user has three options: "Only calculate utilities", "Only summarize utilities", and "Calculate and summarize utilities". Table 5.5 discusses why the user would want to select one option over another.

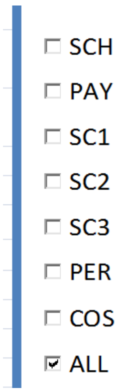

Figure 5.19 - Checkbox options

Table 5.5 - Calculation options explained

Option	**Description**	**Why Select?**
"Only calculate utilities"	The software will automatically calculate the expected utility for each mitigation technique of each root cause for all mission risks.	May want to simply look at the decision tree, and not the summary page.
"Only summarize utilities"	The software highlights the mitigation technique with the maximum expected utility per each root cause, and places this information in a box at the root cause level of the decision tree as well as on the Summary Page	May have already calculated utilities and only want to look at the summary analysis.
"Calculate and summarize utilities"	The software first calculates the mitigation technique expected utilities and then summarizes these on the decision tree and on the Summary Page	This is the recommended option. Calculations and summary information is updated at the same time, relieving any possibility of mismatched information.

Using the data obtained through the examples provided in Step 2 and Step 3, Figure 5.20 shows the resulting Schedule decision tree after selecting the "Calculate and summarize utilities" option. Notice that Mitigation Technique 2 (M2), Build Margin into Scheduled Milestones (as shown in Fig. 5.22), is highlighted in green, signifying that it has the highest expected utility value. This mitigation technique is therefore the technique which, given the probability and attribute parameter values, provides the most effective use of resources. Figure 5.21 shows the Summary page resulting from selecting "Calculate and summarize utilities". Notice that only the second root cause of the Schedule risk has a "Winning Mitigation Technique" and an "Associated Expected Utility". The remaining root causes refer to "No data entered" to remind the user they did not provide data for that portion of the analysis.

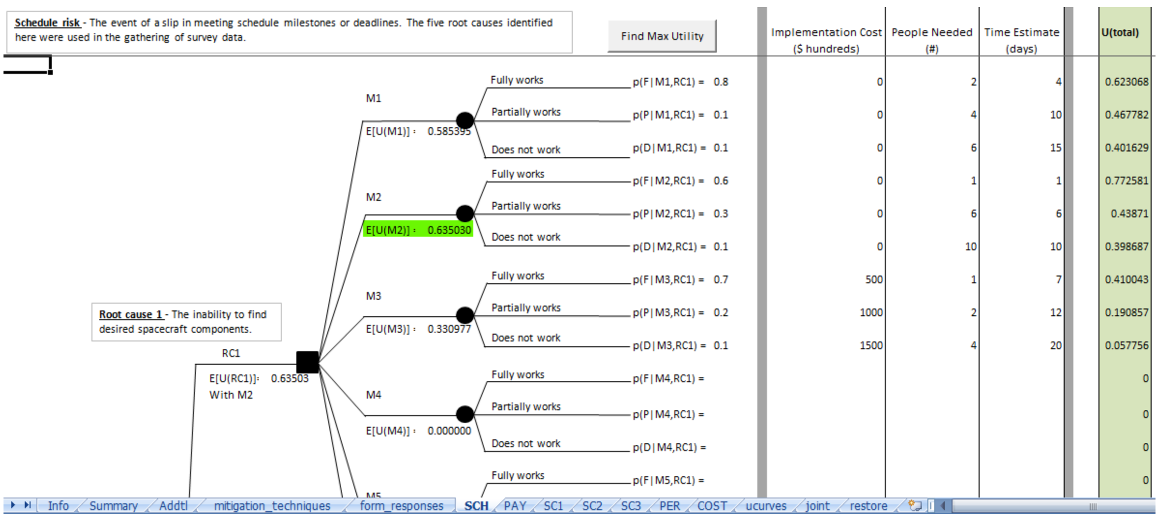

Figure 5.20 - Schedule risk decision tree with calculations

Mission Risk	Root Cause	Winning Mitigation Technique	Associated Expected Utility	Rank w/i Risk	Rank All
Schedule	The event of a slip in meeting schedule milestones or deadlines.				
RC1	Inability to find desired spacecraft components	With M2	0.635030483	1	1
RC2	Mechanical design delays (such as issues with the CAD or drawings)	No data entered	0	2	2
RC3	Software design delays (such as basic component functionality or embedded coding issues)	No data entered	0	2	2
RC4	Delay due to issuse with payload provider (may be related to delivery of EDU or flight unit, documentation, or interface issues)	No data entered	0	2	2
RC5	Delay due to inadequate documentation	No data entered	0	2	2

Figure 5.21 - Summary page with calculations

5.3.6 Step 5: Make the Decision

The user has all the information necessary now to make the decision of which mitigation technique(s) to implement. The results given on the Summary page, shown in Figure 5.21, allow the decision-maker to identify the order in which to apply their resources for a given mission risk using the "Rank w/i [within] Risk" column, or among all root causes using the "Rank All" column. Remember to follow the Rules of Actional Thought described in Section 2.4.3. Namely, the normative and logical decision is to choose to mitigate the root cause with the highest expected utility. This root cause has been calculated to yield the best outcome for the input parameters and the user-defined preference system. Recall that the list of mitigation techniques chosen for analysis is provided on the Mitigation Techniques worksheet, as can be seen in Figure 5.22.

	RC1	RC2	RC3	RC4	RC5	RC6	RC7	Mitigation techniques
Schedule	M1					x	x	formulate schedule milestones with students in mind
						x	x	coordinate between sub-groups/subsystems to ensure each group has necessary information
						x	x	work with payload providers to develop payload schedule and deadlines
	M2					x	x	build margin into schedule milestones
						x	x	maintain updated documentation throughout mission life cycle
	M3					x	x	allocate more resources to the task needing completion
						x	x	*Enter your own mitigation technique #1*
						x	x	*Enter your own mitigation technique #2*
						x	x	*Enter your own mitigation technique #3*

Figure 5.22 - Example mitigation techniques page after calculations

5.3.7 Step 6: Additional Options – Clearing Data

While the software tool may be used fully with Steps 0-5, the user may require the use of the following additional options illustrated in Figure 5.23, and located on the Summary page Options Bar:

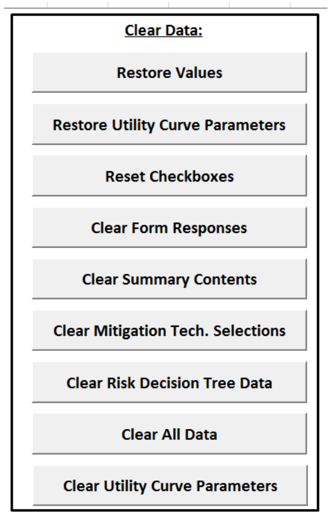

Figure 5.23 - Clearing data options

1. **Restore values** – this option restores values from a case study using the UT-Austin ARMADILLO mission. This option allows the user to see how the tool works without entering any of their own mission-specific data. Additionally, users could simply modify the ARMADILLO data to meet their own mission information. For the ARMADILLO case study inputs and outputs, see Appendix A.

2. **Restore Utility Curve Parameters** – this option allows users to use the pre-set utility curve preferences from the ARMADILLO case study in case they do not wish to enter their own preference data or do not have the time or knowledge to do so. These default parameters are listed in Table 5.6.

Table 5.6 - Default utility curve preferences.

	Cost (USD $)	People (# people)	Time (days)
Max	60000	30	180
Chosen gamma	0.002	0.05	0.1
K values			
K = -0.99156	K1 = 0.9	K2 = 0.75	K3 = 0.7

3. **Reset Checkboxes** – this option clears the checkboxes on the left-hand side of the Options bar. If users are only analyzing a subset of the mission risks, they may wish to clear the checkboxes prior to moving to a different subset of risks.

4. **Clear Form Responses** – this option clears the contents of the Form Responses sheet. Users may want to use this option when they decide to enter a new set of information for analysis.

5. **Clear Summary Contents** – this option allows users to clear the calculated values of the summary page. Users may want to use this if they will be entering new information, so as not confuse old and new results.

6. **Clear Mitigation Technique Selections** – this option allows the user to clear the Mitigation Techniques page of any selections made during the entry of risk information.

7. **Clear Risk Decision Tree Data** – this option will clear the calculated values and input parameters for each decision tree as indicated by the checkboxes. For example, if the "All" checkbox is selected, "Clear Risk Decision Tree Data" will clear the data on all the decision tree pages.

8. **Clear All Data** – this function clears the form responses, summary contents, mitigation technique selections, and decision tree data. It is advised to only use this when analyzing a completely new set of data.

9. **Clear Utility Curve Parameters** – this option will delete the default or user-entered utility curve parameters. This function is included in the "Clear All Data" button, but is also available as a stand-alone command.

Note: The analysis cannot occur without some specific data:

- Probabilities and input values for the mitigation technique/root cause combinations the user wishes to analyze.
- Utility curve parameters. The user may use the default utility curve parameter settings by selecting the "Restore Utility Curve Parameters" options mentioned above. Then, they could modify the settings by examining the "ucurves" worksheet within the tool. If the user tries to complete analysis without having entered utility curve preferences, a message box will pop up requesting they complete this step. Any calculations displayed should therefore be ignored until the data has been properly entered.

5.3.8 Step 7: Additional Options – Analyzing Data

While the software tool may be used fully with Steps 0-5, and the additional items of Step 6, the user may wish for the analysis options illustrated in Figure 5.24 and located on the Summary page Options Bar:

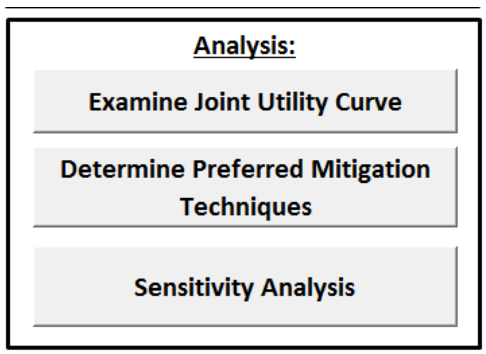

Figure 5.24 - Analyzing data options.

1. **Examine Joint Utility Curve**

This option will direct the user to the "joint" worksheet where there exists an interactive plot similar to the one shown in Figure 5.25. The user must enter the number of people for which they wish to view the joint utility curve in order to hold one attribute constant for viewing in a 3-D manner, and then select the "PLOT!" button. Recall that the joint utility curve gives the user's preference system with respect to all three variables – cost, people, and time – required for a given mitigation technique. This plot details the importance of certain values of the cost, people, and time parameters. The user may determine the utility of any given set of parameters by examining the data table.

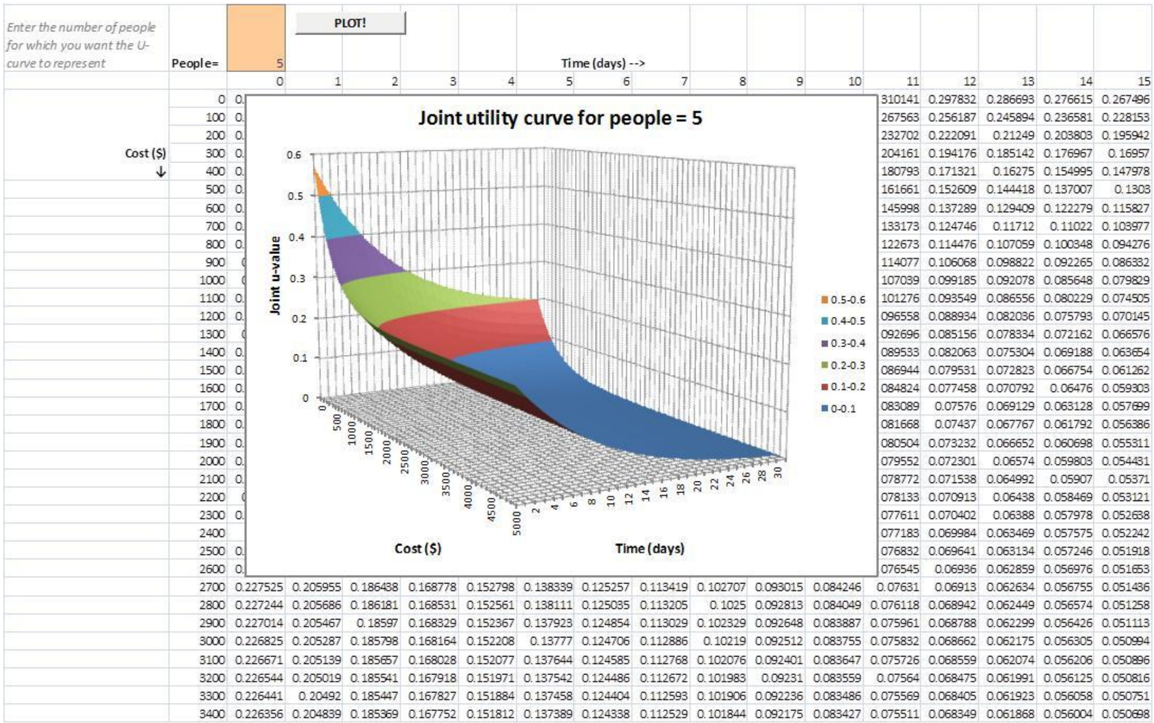

Figure 5.25 - Joint utility curve.

2. **Determine Preferred Mitigation Techniques**

This option directs the user to the Additional (“Addtl”) page where the mitigation technique preferred the most number of times within a mission risk is displayed, as shown in Figure 5.26. This helps the user determine if there are any mitigation techniques which would be useful across the entire mission risk, not just for a given root cause. Note that the displayed mitigation technique should match with the mode for each mission risk category of the “Winning Mitigation Technique” column of the Summary page. The example shown in Figure 5.26 reflects the results of the ARMADILLO case study.

	Mitigation technique summary
SCH	The most preferred mitigation technique for the SCH risk is: M6
PAY	The most preferred mitigation technique for the PAY risk is: M2
SC1	The most preferred mitigation technique for the SC1 risk is: M4
SC2	The most preferred mitigation technique for the SC2 risk is: M5
SC3	The most preferred mitigation technique for the SC3 risk is: M1, M2, M3, M4
PER	The most preferred mitigation technique for the PER risk is: M4
COST	The most preferred mitigation technique for the COST risk is: M3

Figure 5.26 - Mitigation technique summary.

3. **Sensitivity Analysis**

This option requires the user to first indicate which risks they wish to analyze by checking or un-checking the checkboxes within the Options panel. A few key notes, the reader is requested to pay extra attention to the third bullet:

- The more risks selected, the longer the analysis will take.
- Because of limitations with Excel, not all seven risks can be selected at once for the sensitivity analysis. It is suggested to run multiple analyses, so as not to lock the computer for too long. While it is possible to complete other work while the analysis is running, it is not possible to use Excel at the same time.
- **Running the sensitivity analysis multiple times will overwrite the output file, so make sure to save the desired output file as a different name if multiple analyses are to be completed.**
- Two output workbooks will be created as a part of the program. These files will be stored at the same location as where the software tool itself has been stored. These output files are named: "sensitivity_analysis_Mi_results.xls" and "sensitivity_analysis_U_results.xls."

The sensitivity analysis looks at the user's input and determines how the output would be affected if the user's preferences were slightly different. That is, the program re-calculates the decision result with different u-curve preference information in the form of varying k and gamma values. Recall that the k values are used to combine the individual parameter utility functions while the gamma value is a parameter of the utility function itself.

The "Addtl" page of the Decision Advisor software tool includes, as a reference, the different combinations of gamma and k values used in the sensitivity analysis for the specific user. These values are also located on the first page, "Parameters," of the two output workbooks, "sensitivity_analysis_Mi_results" and "sensitivity_analysis_U_results."

The sensitivity analysis is meant to provide the user a sense of how their decision would change if their preference system was slightly different. The software has been limited to four values of the gamma parameter for each cost, people, and time. Thus, there are 64 combinations of gamma parameters which are studied for the sensitivity analysis. The k values used in the sensitivity analysis depend upon the user's completion of the "Enter joint utility preferences" step. The program takes each individual k_1, k_2, k_3 and uses three values below and three values above, in increments of 0.1, with a minimum value of 0 and a maximum value of 1 as the k value parameters for the sensitivity analysis. So, if the user had a k_1=0.72, k_2=0.6, k_3=0.9, then the values used in the sensitivity analysis would be those shown in Table 5.7. Because there are seven options for each k_1, k_2, and k_3, there are 343 different k value combinations.

Table 5.7 - Example k values for sensitivity analysis.

	Call sign	k_1	k_2	k_3
-0.3	-3d	0.42	0.3	0.6
-0.2	-2d	0.52	0.4	0.7
-0.1	-1d	0.62	0.5	0.8
Base	0d	0.72	0.6	0.9
+0.1	1d	0.82	0.7	1
+0.2	2d	0.92	0.8	1
+0.3	3d	1	0.9	1

The output workbooks will contain the data set itself, as well as several useful plots and summaries. The first page a user will see when opening the output workbook is the "Parameters" page, which lists the gamma and k values used in the analysis as well as the trial reference number used in some of the output plots. Note that to open the output workbooks, users may have to select "yes" when asked if they wish to open a file with a different extension. This appears to be due to the VBA programming of opening and closing the workbooks. It should be safe to select "yes."

After the "Parameters" page will be a page for each mission risk root cause. If multiple mission risks were selected, all root causes for those multiple mission risks should be displayed as separate worksheets. For the workbook, "sensitivity_analysis_Mi_results" the output will be the mitigation technique number which maximizes the utility of that root cause of the given mission risk. Similarly, the output of the "sensitivity_analysis_U_results" is the maximum utility value for the root cause of the given mission risk. Thus, the plot which overlays the data set represents the output value as a function of the k and gamma value trials. Recall the trial number and associated values can be found on the "Parameters" worksheet. An example plot is shown for Schedule Root Cause 1 in Figure 5.27. Note that this plot is not the result of running the sensitivity analysis on the example from Steps 1-5. This plot shows the oscillation between the mitigation techniques 3, 4, and 6. Obviously, the 6th mitigation technique is chosen much less frequently. In the example shown in Figure 5.27, the Schedule Root Cause 1 output tends to fluctuate between Mitigation Technique 3 and 4 much of the time. This fluctuation is most likely due to the specific set of k and gamma values, and it would be incumbent upon the user to determine which cases, located behind the plot, result in a specific mitigation technique. The plot and numerical sensitivity analysis output are purely meant to help the user identify how their decisions would change if their utility preferences were slightly different. The highlighted formatting represents an example of post-processing the user could complete. That is, if they wish to look for which trials yield a certain mitigation technique, then they could use the Excel conditional formatting options.

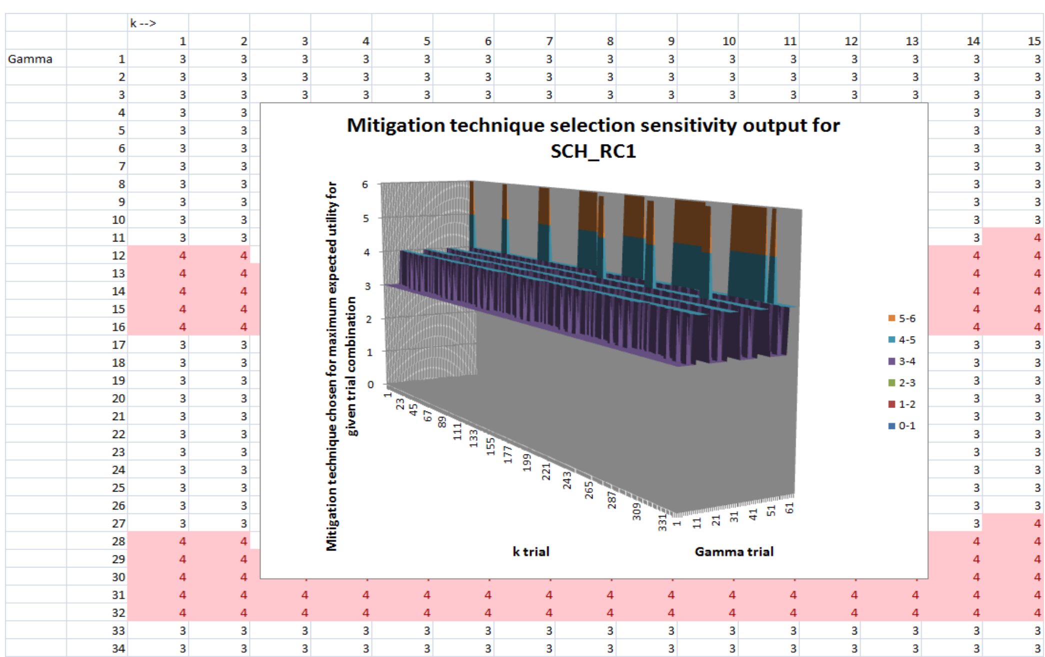

Figure 5.27 - Sensitivity analysis results example.

The second set of plots displayed for each mission risk root cause are shown in Figure 5.28. These plots count the number of times the output value falls within a certain utility range or is equal to a given mitigation technique, depending on the output value, for the set of trials which vary individual parameters. The utility ranges have an inclusive lower bound, but exclusive upper bound, i.e. [0.2, 0.4). As an example, the user may be interested in the sensitivity output if only the k_1 value was changed, or if only the gamma parameter for the People input value was changed. These plots allow the user to determine how big of an impact an individual preference parameter has on the decision outcome.

Columns with the titles, "-3d," "-2d," etc., indicate the change in the given parameter, as detailed with an example in Table 5.7. For example, within the K1 section of Figure 5.28, "-3d" means that the values in that column correspond to when k_1 was equal to -3 times the delta value, in this case 0.1. By examining either the histogram data output or the graphical display, users can see how changing a given utility function parameter may affect either their mitigation choice or the maximum expected utility associated with the mitigation choice. As an example, the K1 section of Figure 5.28 shows that the expected utility is consistently between 0.2 and 0.8 and only dips below 0.2 when k_1= "-3d" or "-2d." Additionally, when no change is made to k_1, the utility value tends to be in the [0.4, 0.6) range. However, when increased or decreased slightly, the utility value becomes more spread out. This is more evident in the lower ranges of $k_1$than the increased value range.

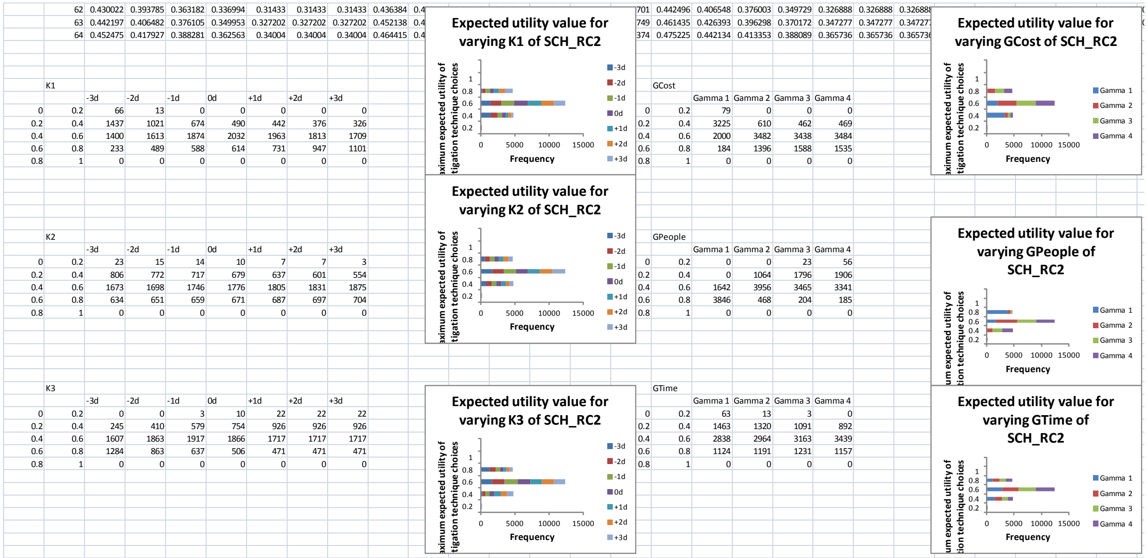

Figure 5.28 - Individual histogram sensitivity analysis example output.

The usefulness of the tool is negated if it cannot be shown to produce meaningful results in many different situations. Just as with the CubeSat Risk Analysis software tool, the Decision Advisor tool must be thoroughly tested and validated prior to being released to the small satellite community. The next chapter presents the testing and validation methods used in this analysis.

Chapter notes:

1 Brumbaugh, K.M., Lightsey, E.G. "Systematic Approach to Risk Management for Small Satellites." *Journal of Small Satellites* 2 (2013): 147-160. Web.

2 Gamble, K.B, Lightsey, E.G. "CubeSat Mission Design Software Tool for Risk Estimating Relationships." *Acta Astronautica* 102 (2014): 226-240. Web.

3 "Risk Management Guide for DoD Acquisition, 6th ed." Department of Defense. August 2006. Web. 11 Feb 2015.

Chapter 6: Testing of CubeSat Decision Advisor Software Tool

Since there is no inherent data set associated with the Decision Advisor with which to test the assessment accuracy of the tool, and no similar existing tool is readily accessible, validation and testing is completed via case study analysis. Mathematically simple cases provided a method of error-checking the software to ensure that known results were obtained when the associated inputs were supplied. Sensitivity analysis supplied insights into how the decisions would change should a parameter only slightly deviate from its nominal value. Monte Carlo analysis investigated the effect of different combinations of parameters on the chosen mitigation technique and expected utility value. A series of case studies were completed based on data from the ARMADILLO 3U CubeSat mission to illustrate the impact this software tool can make on a mission at any point of its development cycle. Finally, the software tool has been released to the Small Satellite community with a request to return feedback in addition to the data input and resulting conclusions for further case study material.

6.1 Mathematically Simple Cases / Error Checking

Before running more detailed validation and testing cases, it was necessary to ensure that the software tool was properly functioning. To do this, a series of mathematically simple or error-checking cases were devised. These cases consisted of inputs which would nominally yield a set of obvious outputs, if the software tool was working appropriately. Because both the inputs and nominal outputs were known, the accuracy of the tool could be established. The following test cases were initially built and tested on the Schedule mission risk, but were later tested on the remaining mission risks to ensure the entire tool functioned appropriately.

6.1.1 Missing or inappropriate data

The tool must be able to handle missing or blank data, since the user may wish to only analyze a single risk or root cause. As such, test cases were created to test whether or not the tool would flag missing data as an error. One test case focused on the Schedule risk and provided inputs for two mitigation techniques (MT) associated with root cause (RC) 1, one MT with RC2, RC3 and RC4 were left blank, and two MTs associated with RC5. Thus, both data left blank within the root cause as well as whole root causes left blank were tested. The result was that the software tool treats missing data as if it is a zero value and indicates on the Summary page that no data was entered. It should be noted that a probability value may be left blank only if the remaining values sum to unity, or no data for the mitigation technique is entered. However, cost, time, and people input parameters may be left blank at any time. Another test case examined the outcome should a user leave the utility preferences blank. Since these values are necessary to determine the expected utility, the tool was initially unable to calculate the utilities and returned an error message. After implementing this test case, a feature was added so that when the user selects the calculation option, the tool automatically checks to make sure all the appropriate utility preference data has been entered. If any of the utility values are missing, then a message box appears with the missing data listed.

The input parameter user interface also checks to ensure the values are numeric. If a user enters a non-numerical value, e.g. $, %, *, then a message box appears when the user tries to Save the input parameters. The message box lists the boxes which contain a non-numerical value and the user is asked to change the values entered.

6.1.2 Maximum and Minimum Input Values

Because of the way the attribute utility functions are scaled, a maximum attribute parameter would yield a utility value of zero while a minimum attribute parameter would yield a utility value of one. Similarly, if all the attributes were at their maximum, then the joint utility would be zero. If all the attributes were at their minimum values, then the joint utility value would be one. These relationships provide a set of test cases to ensure that the utility values are properly calculated. A set of maximum values is shown in Table 6.1. The minimum values are all zero, since it is not reasonable to have negative cost, people, or time.

Table 6.1 - Set of maximum input parameter values.

	Cost (USD $)	People (# people)	Time (days)
Maximum value	5000	10	20

A first test case used all maximum values to ensure that the resulting utility calculations were all zero. Figure 6.1 shows the decision tree result of this all-maximum value test case. Notice that the far right column consists only of zeros and the expected utility value is also zero. The far right column, though, is the joint utility. This joint utility value will only be zero if all the attribute values correspond to the maximum values as indicated by the user. A similar test case was developed to test the tool response when all the minimum input parameters, namely all zeros, were entered. The result was a set of utility values equaling one, as expected. A final set of test cases employed involved testing inputs which go above and below the maximum and minimum values indicated by the user. Going above the maximum value simply resulted in a negative utility. A negative utility value is not impossible; it simply indicates that the parameter is not acceptable given the user's preferences. An input value less than the minimum, namely a negative value, results in a message box during parameter entry indicating the user must supply a different value.

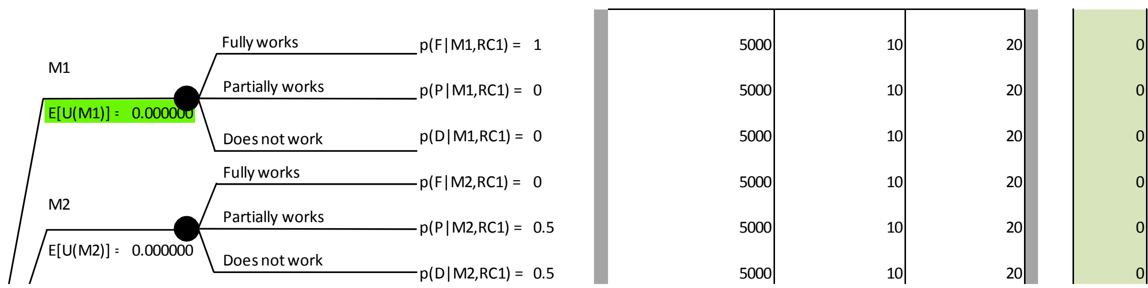

Figure 6.1 - Example maximum value test case decision tree result.

6.1.3 Modifying utility curve parameters

The utility curve parameters describe the user preference of a specific attribute – cost, people, or time. A set of test cases were devised to test how the software tool would react when these utility curve parameters were altered. In a way, these test cases comprised a controlled sensitivity analysis, because specific combinations of the gamma parameters were used in order to determine if changing the gamma values in a known fashion would result in a predicted outcome.

Table 6.2 shows the individual utility values for each gamma changing case. Case 1 involved changing the cost gamma value while Case 2 changed the people value and Case 3 changed the time value. Recall that the decision tree incorporates three outcomes of the mitigation technique: either it fully works, partially works, or does not work. Note that each outcome is defined by the user. That is, each user could have a different definition of what it means for a technique to fully work. The baseline shows the starting utility values for the case that the technique fully works. The Cost, People, and Time sections contain only their attribute utility value. For example, the Cost section values are only the cost utility values, since the other input parameters did not change and the utility value therefore stays the same. From this data, it is seen that as the gamma parameter is decreased (increasing case letters a-b-c), the utility value increases as expected.

Table 6.2 - Utility values interaction due to changing gamma values.

	Baseline			Cost	
Cost	**People**	**Time**	**Case 1a**	**Case 1b**	**Case 1c**
0.980199	0.367879	0.904837	0.99005	0.995012	0.999
	People			**Time**	
Case 2a	**Case 2b**	**Case 2c**	**Case 3a**	**Case 3b**	**Case 3c**
0.606531	0.740818	0.904837	0.951229	0.97531	0.99005

The utility functions, such as the People functions in Figure 6.2, show that with a lower gamma value, the same input parameter will yield a larger utility value. All other values being the same, it would be expected that with a decrease in the gamma parameter would see higher utility values. However, this is only true in the joint utility values for decreasing the people gamma. In fact, the utility values decrease in the cost gamma case, and mostly increase in the time gamma cases. Given the output of Table 6.2 and the associated discussion, the non-increasing trend must be due to the interaction between all three of the cost, people, and time input parameters.

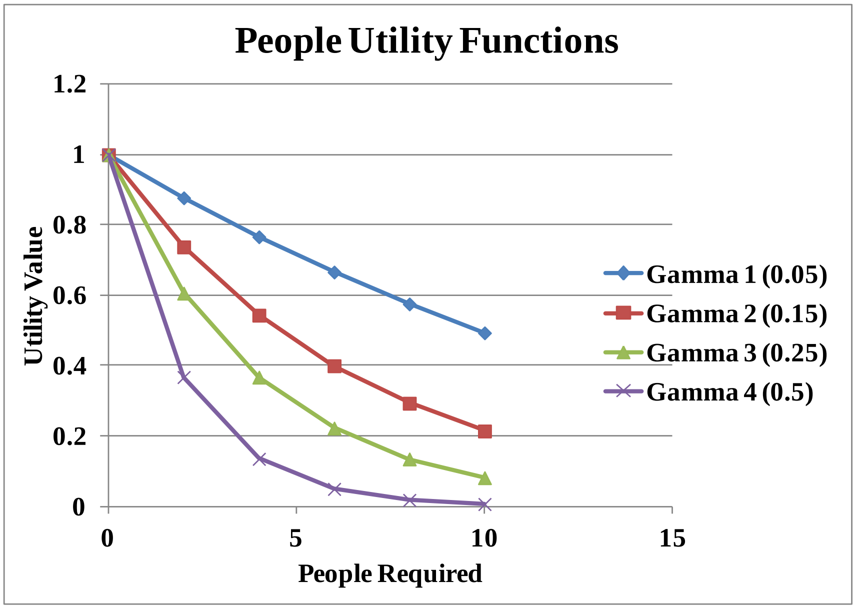

Figure 6.2 - People utility functions for varying gamma parameters.

6.1.4 Modifying gamma and input parameters

Since the equations for the attribute utility functions are negative exponential curves, as the exponent increases, the utility value decreases. While the previous section outlined a set of test cases which studied the effects of changing only the utility curve parameter, gamma, a separate set of test cases were created to test the combined effect of changing both the gamma parameters and the attribute input values: cost, time, and people. Four test cases were created using large and small gamma and input values, as shown in Table 6.3. These four test cases consisted of the (A) large gamma-small input, (B) large gamma-large input, (C) small gamma-large input, and (D) small gamma-small input. The large gamma-large input should yield the smallest utility value while the small gamma-small input value should yield the largest utility value.

The results for this test are given in Table 6.4. As expected from theory, when both the gamma and input parameters are small, the highest joint utility value is observed.

Similarly, when both the gamma and input parameters are large, the lowest joint utility value is obtained. These values were first calculated by hand for the software tool to verify. The tool matched the calculations exactly.

Table 6.3 - Changing both gamma and input values.

	Cost (USD hundreds $)	People (# people)	Time (days)
Small Gamma	0.0001	0.05	0.01
Large Gamma	0.002	0.5	0.1
Small input	5	2	1
Large input	10	6	10

Table 6.4 - Changing both gamma and input values results.

	Cost	People	Time	Joint
A	0.9900	0.3679	0.9048	0.6502
B	0.9802	0.0498	0.3679	0.2954
C	0.9990	0.7408	0.9048	0.6040
D	0.9995	0.9048	0.9901	0.8842

6.2 SENSITIVITY ANALYSIS

By conducting a sensitivity analysis, it is possible to determine how the choice of mitigation technique is subject to change given a slight modification of preferences. This is particularly insightful because users may realize during the course of inputting their data that they had misrepresented their preferences. Namely, how they value cost, people, and time. Because of the infinite combinations of inputs, an assumed set of probabilities, cost, people, and time parameters were held constant throughout the sensitivity analysis. Additionally, only one risk, Schedule, was analyzed, since the same attribute inputs on other mission risks would yield the same output. Instead, the utility function k values and gamma parameters were varied in order to examine how changing preferences would change the decision analysis outcome. Modifying all of the parameters will be described in the Monte Carlo Analysis section.

With four gamma parameters for each of the three attributes, 64 different gamma value combinations were possible. To ensure computing capability, k_i value combinations were also limited to values between 0.2 and 1 in increments of 0.2. Thus, with three attributes, there were a total of 64 k_i value combinations. The k value is then dependent upon the three k_i values according to Equation (2.9). A software program stepped through each gamma and k value combination and calculated the winning choice of mitigation technique and its associated expected utility for each root cause within the Schedule risk.

Recall the probabilities and attribute values were constant for all gamma and k value combinations. Thus, the result shows only the effect of changing the gamma and/or k values in the utility function calculations. That is, the results relate to changing the utility curve or the manner in which the utility curves are combined. The histograms shown in Figure 6.3 and Figure 6.4 illustrate the number of times a certain combination of k or gamma values, respectively, yielded the maximum expected utility. The more spread out the root cause is on the histograms of Figure 6.3 and Figure 6.4, the more susceptible the root cause is to fluctuations in gamma or k values. Particularly, a slight change in a user's preference will yield a different mitigation technique and expected utility result. As illustrated in Figure 6.3 and Figure 6.4, Root Cause 3 and Root Cause 5 appear to be the most unstable due to their more varied distributions than the other root causes. Specific to the Schedule risk, Root Cause 3 is "Software design delay (such as basic component functionality or embedded coding issues)" while Root Cause 5 is "Delay due to inadequate documentation." When compared to the other Schedule root causes, it would make sense that these two root causes would be sensitive to small changes in preference systems and input values, since both are highly dependent upon circumstances. However, the sensitivity data is specific to the unique test case. Results may vary for other users. The sensitivity seen in this example could be explained by the input parameters of those specific root causes. In other words, the combination of probabilities and attribute values affects the utility values, and a slight change in gamma and k values may sway the mitigation technique choice.

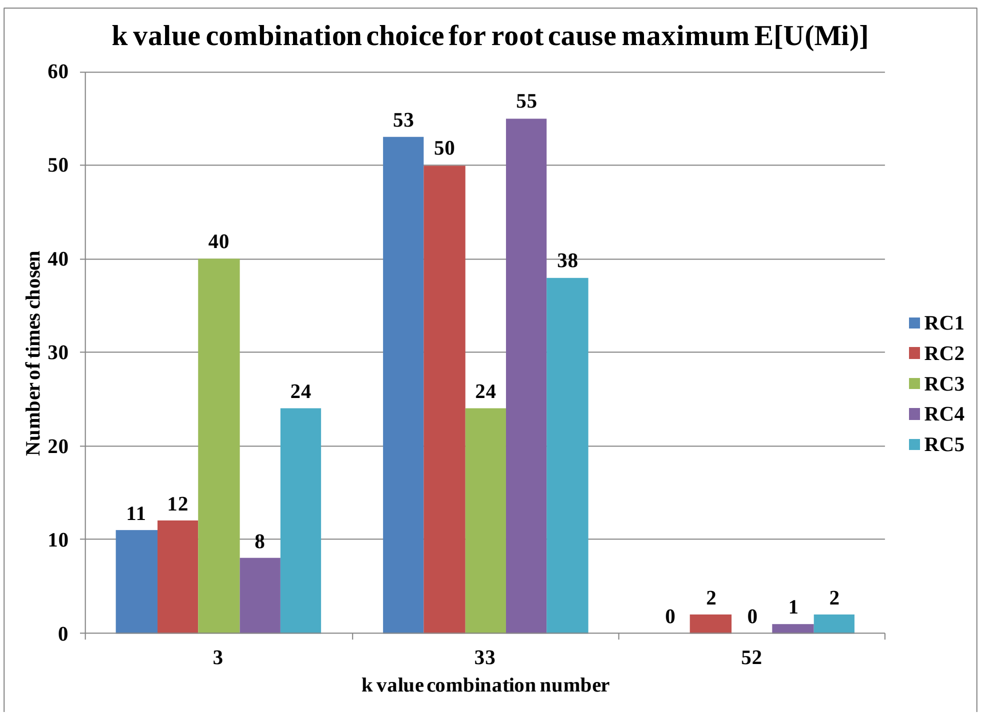

Figure 6.3 - Histogram of k combination yielding maximum expected utility.

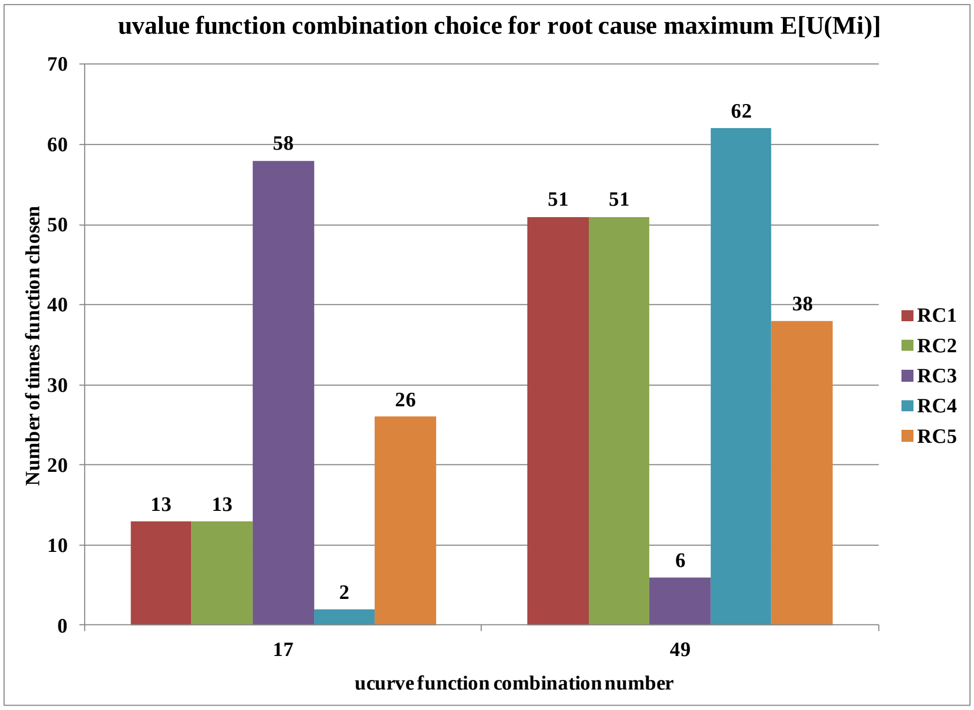

Figure 6.4 - Histogram of gamma combinations yielding maximum expected utility.

Figure 6.5 and Figure 6.6 show a more detailed picture of the maximum expected utility values as a function of the gamma and k value combination trials. Across the ucurve combo trials in Figure 6.5, there is a 16 data point period – after 16 combinations, the first ucurve function is moved to the next parameter value, and the program continues to go through other parameters possible values. Clearly, the maximum expected utility value occurs at any combination of the first ucurve (representing cost) and the first (smallest) option of the other ucurve parameters (time, people). Conversely, when the non-cost parameters are their last (largest) options, the expected utility will be at its minimum. Interestingly, there is more variation when changing the ucurve parameters, shown in Figure 6.5, than when the k values are changed, shown in Figure 6.6. Both the ucurve and k value combination analyses have short and long periods corresponding to the change in parameters.

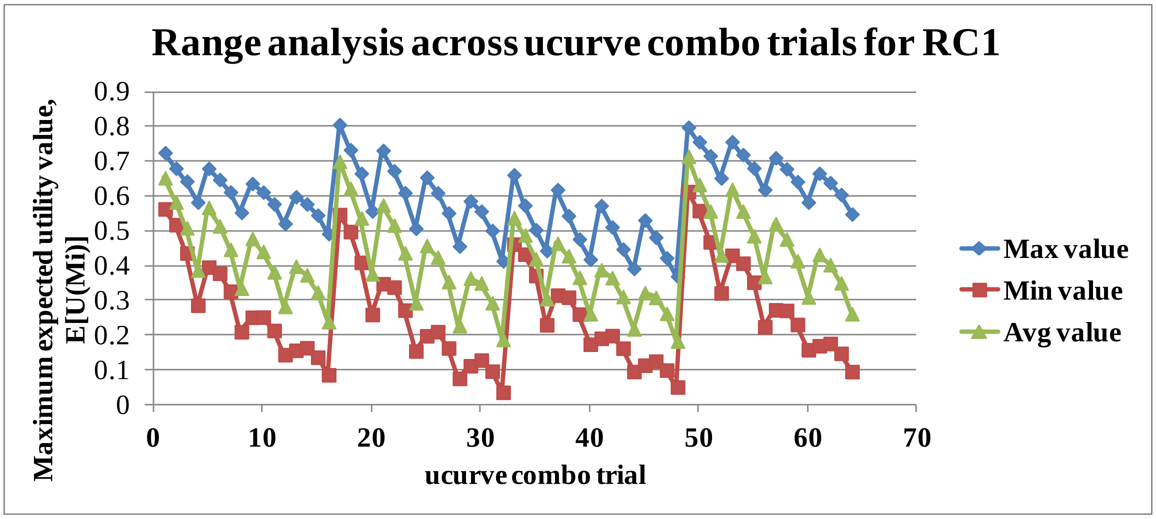

Figure 6.5 - Maximum expected utility for Root Cause 1 as a function of the gamma combination trials.

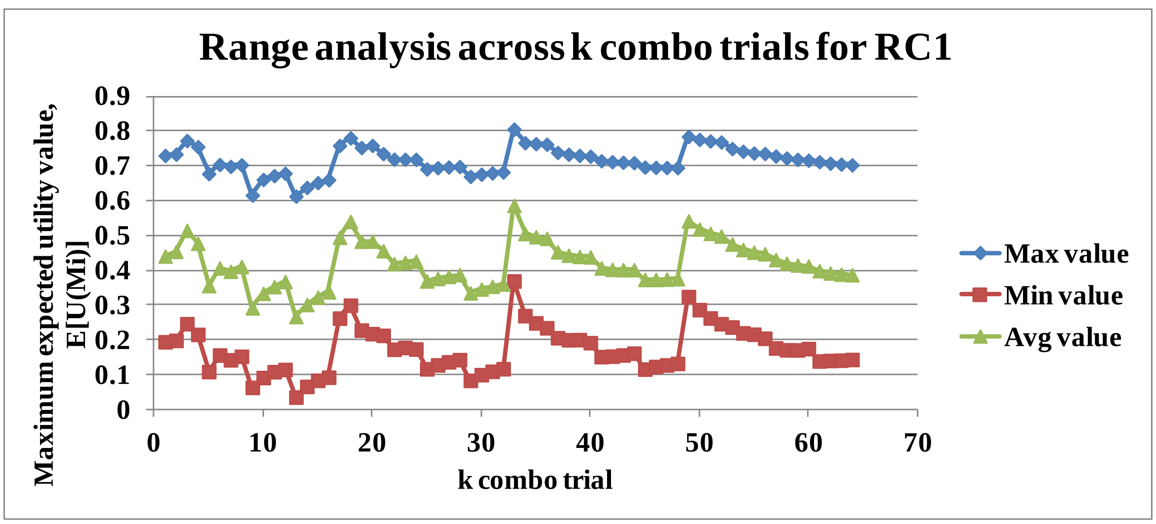

Figure 6.6 - Maximum expected utility for Root Cause 1 as a function of the k combination trials.

This sensitivity analysis was based on a pre-determined set of input parameters as an effort to see how the software tool would handle parameters changing by incremental amounts. The result was satisfyingly interesting that a sensitivity analysis capability was built into the tool so that users may produce their own sensitivity analysis to see how their decision could change if their preferences were slightly different. The sensitivity analysis tested the decision analysis output dependence upon the input parameters. There are levels of interaction due to the attribute utility values being a function of multiple inputs, and the joint utility value being a function of the attribute values with additional inputs. All in all, the sensitivity analysis provides insights into how the decision may change should user preferences slightly vary.

6.3 MONTE CARLO ANALYSIS

While the sensitivity analysis looked at only changing the gamma and k values while keeping a set of input parameters constant, the Monte Carlo simulation changed the input parameters as well. The same 64 combinations of gamma and k values were used in this analysis as in the sensitivity analysis. Additionally, 21 probability combinations were created based on probabilities ranging from 0 to 1 in increments of 0.2. A constraint of probabilities summing to unity was applied to these probabilities, thus the 21 combinations of probabilities. Cost was varied from \$0 to \$5000 in increments of \$500. The people parameter was varied from 0 to 10 in increments of 2. Time was varied from 0 to 30 days in increments of 5. Therefore, there were a possible 11 cost, 6 people, and 7 time values. Between the probability, attribute, gamma, and k values, there were on the order of 10^{12} possible combinations for a single mitigation technique. Therefore, modeling an entire risk was out of the question, and the Monte Carlo analysis focused on modeling the parameter choices for a single mitigation technique. Additionally, the results from a single mitigation technique are applicable to the remaining techniques across all of the mission risks.

The purpose of the Monte Carlo simulation was to model the decision analysis outcome for the possible sets of inputs. To aid in computational intensity, it is often helpful to generate Monte Carlo samples in a number of runs. Samples are the data points used in analysis, but are drawn from distributions during the run. Runs are a way of organizing these samples. This Monte Carlo analysis used 100,000 samples. Rather than sample 100,000 times during a single run, it is often more computationally advantageous to spread the samples across numerous runs. This analysis used 100 runs of 1000 samples, yielding the desired 100,000 samples. Figure 6.7 illustrates how the simulation was completed, including the variables which were sampled, determination of the utility values as well as calculation of expected utility, and outputting the key statistics for analysis. Furthermore, Figure 6.7 shows the relationship between samples and runs. The decision analysis outcome is based on the maximum expected utility. For each run, the inputs resulting in the maximum expected utility were stored as well as plotted. In this way, analysis could be completed on an individual run as well as an aggregated basis.

Since no prior distribution was imposed on the input parameters, the Monte Carlo simulation should call upon each parameter an approximately equal number of times, in other words, using a uniform distribution. This should be true both in terms of an individual run as well as the entire compilation of data. Figure 6.8 shows the approximately even distribution of cost, people, and time parameters chosen on an individual run basis. The aggregate data shows a similar trend.

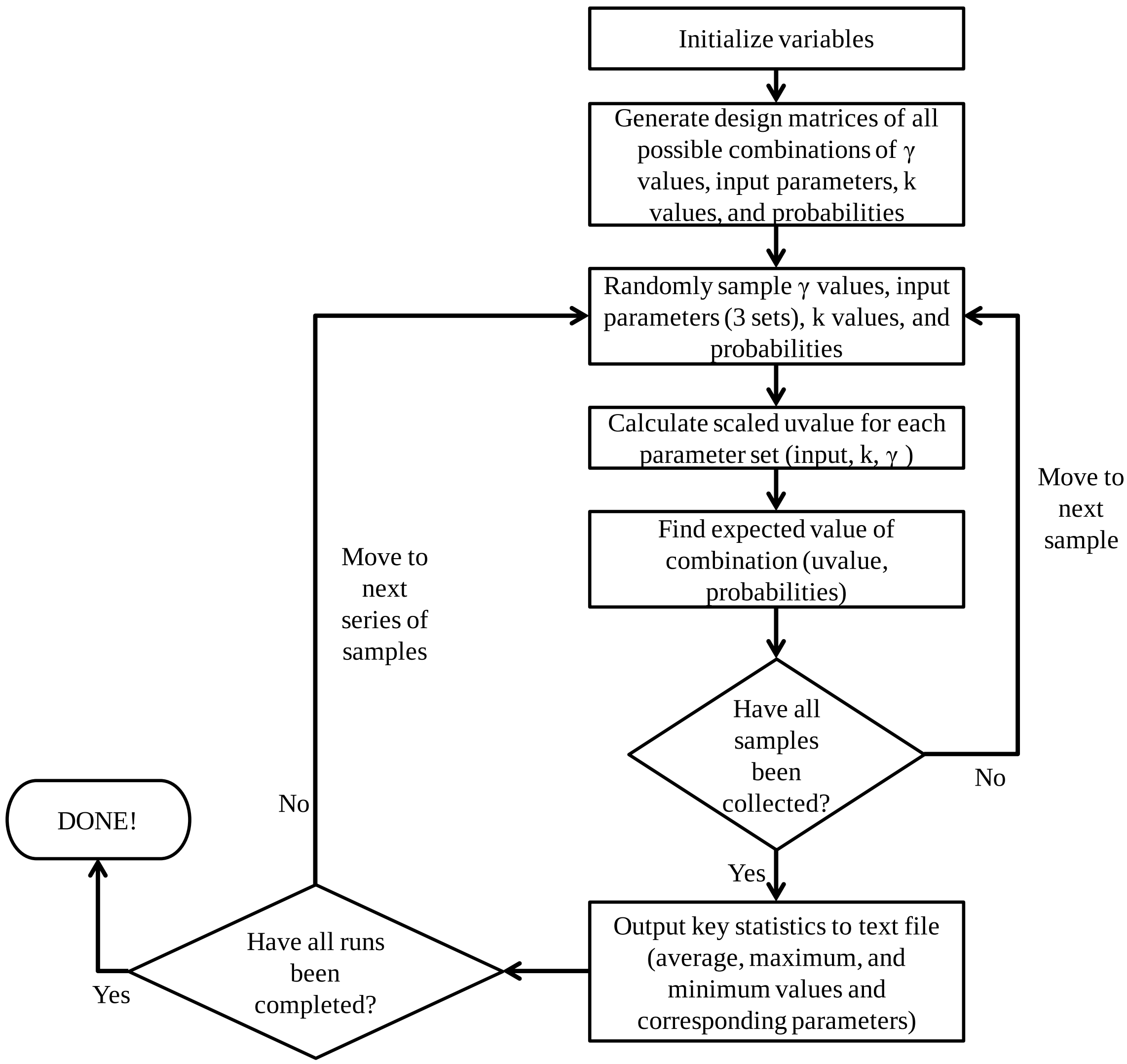

Figure 6.7 - Monte Carlo simulation flowchart.

The sensitivity analysis of the previous section assessed the effect of input parameters on changing the expected utility value and the mitigation technique choice. The Monte Carlo simulation is an effort to validate the decision theory applied in the software tool. In other words, the simulation shows that certain combinations of parameters yield the maximum expected utility as expected from decision theory. Matching theory, the minimum possible attribute parameters yielded most of the maximum expected utility values, as shown in Figure 6.9 for the cost parameter. Similar plots exist for the people and time parameters. Note that the minimum value does not always provide the maximum expected utility. The other values may at times provide the maximum expected utility due to the other input parameters and the utility preference information. For example, if cost is not preferred as highly as people, then a higher cost value may be offset by a lower people value. Additionally, probabilities can play a significant role in a larger attribute value still resulting in a maximum expected utility.

The Monte Carlo simulation showed that the decision theory applied in the tool was working properly. Results were obtained which match theory. Namely, lower input parameters, higher probabilities on lower input parameters, or lower probabilities on higher input parameters are more likely to generate maximum expected utility values.

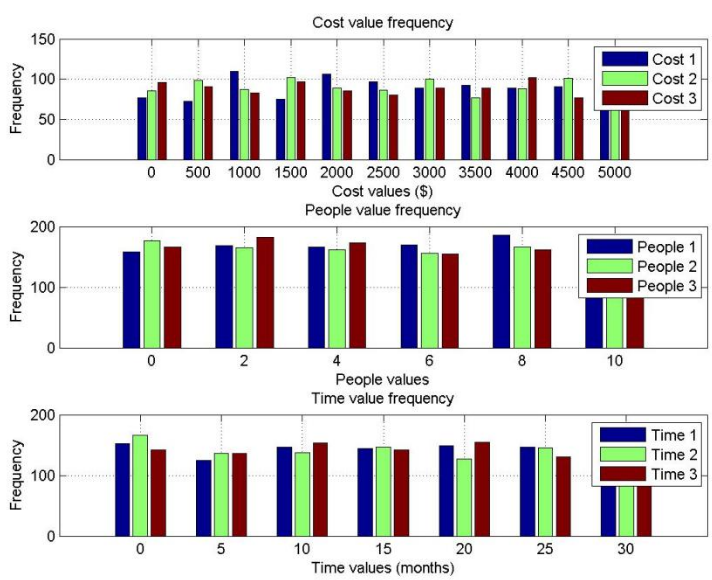

Figure 6.8 - Individual run histogram of cost, people, and time parameters chosen for the Monte Carlo Simulation.

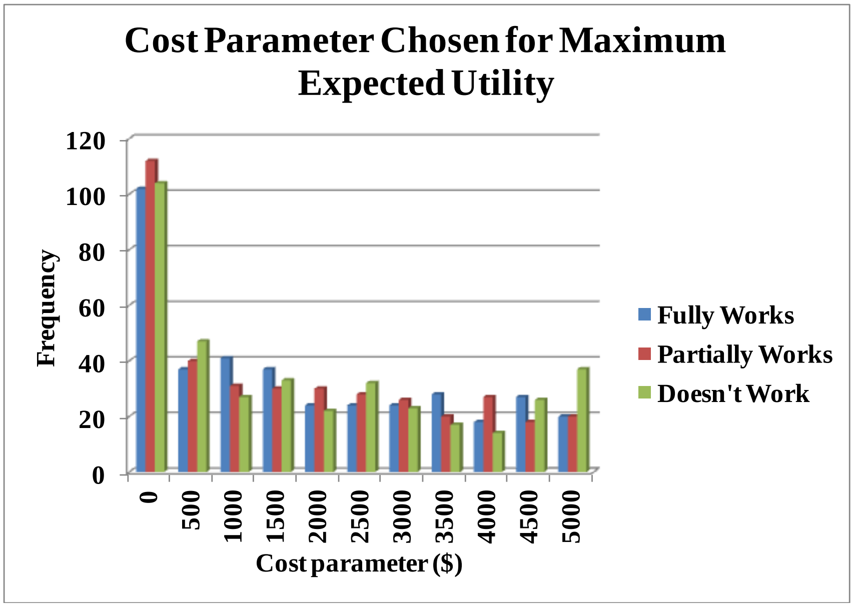

Figure 6.9 - Cost parameter chosen in Monte Carlo simulation for the maximum expected utility value.

6.4 TEST CASES

The mathematically simple cases, sensitivity analysis, and Monte Carlo simulation were all based on artificial data. Case studies show the capability range of the Decision Advisor tool. The ARMADILLO case study provides a real-world example of a current mission in the TSL and the associated inputs a systems engineer would enter into the Decision Advisor tool. The life-cycle case study goes through four phases of a spacecraft life-cycle: development, integration, testing, and operations. In each of these phases, the ARMADILLO case study data is modified to reflect how a systems engineer would view the parameters at a given stage of the spacecraft development. By examining each of these life-cycle phases, it is shown that the Decision Advisor can be used for all phases of a spacecraft mission and reflect appropriate results.

6.4.1 ARMADILLO Case Study

A case study was created using the ARMADILLO 3-Unit CubeSat mission, described in Section 1.4.4 with input parameters current as of September 2014. The full set of inputs can be found in Appendix A as well as the Decision Advisor User's Guide. Analysis of the output resulted in Table 6.5 in which the overall top five mitigation techniques are listed. These are the mitigation techniques across the seven mission risks with all 32 root causes which would be most advantageous to mitigate given the user's preferences. Interestingly, applying the CubeSat Risk Analysis software tool detailed in Chapter 3 to the ARMADILLO mission in its current status resulted in the identification of the COST and SCH risks as the highest concern. Table 6.5 shows four methods to help mitigate several of the root causes to combat these highest concern risks. PER was the lowest concern, but it obviously has one of the easiest and most worthwhile root causes to mitigate according to Table 6.5. The Loss of Hardware root cause was deemed a personnel risk because of the possibility that team members may not adequately track their handling of hardware and the team may physically lose the hardware or it may be damaged without knowing the reason. A simple mitigation technique to implement is to introduce a hardware tracking method such as certification logs. This mitigation technique seems to work well for the Texas Spacecraft Lab.

Table 6.5 - Top five mitigation techniques for ARMADILLO case study.

Mission Risk	**Root Cause**	**Explanation**	**Mitigation Technique**	**Expected Utility**	**Overall rank**
COST	RC2	COTS component price increases	Include contingency in budget allocations	0.893	1
COST	RC1	Incomplete understanding of projected total mission costs	Include contingency in budget allocations	0.879	2
SCH	RC1	Inability to find desired spacecraft components	Allocate more resources to the task needing completion	0.871	3
SCH	RC2	Mechanical design delays	Allocate more resources to the task needing completion	0.871	3
PER	RC2	Loss of hardware	Have tracking method for hardware (e.g. inventory system, certification logs)	0.856	5

A sensitivity analysis was completed on the ARMADILLO case study data to show how the results would be affected by small changes in the utility curve parameters. Interestingly, of the top five root causes to mitigate, as described in Table 6.5, the COST RC1 and RC2 both had no variation in the mitigation technique selected for maximum utility. This indicates that no matter the combination of utility preferences, the mitigation technique listed will remain the best choice for the defined input parameters. Additionally, the maximum utility value for the COST RC1 and RC2 showed little variation, implying that these two root causes would consistently be ranked among the top root causes to mitigate.

The Schedule risk showed more deviation in both mitigation technique chosen and expected utility. Figure 6.10 shows the variability in the chosen mitigation technique across different values of utility preferences (gamma trial) and methods in which these preferences were combined (k trial). Figure 6.11 illustrates the same variability in the maximum expected utility value associated with the chosen mitigation technique. The Schedule RC2 root cause showed similar variability in both chosen mitigation technique and associated expected utility. Plots similar to Figure 6.10 and Figure 6.11 are available for the other root causes, but are not shown here.

The variability shown in Figure 6.10 is mostly between mitigation techniques 3 and 4, with occasional jumps to mitigation technique 6. Figure 6.11 is much more variable, but with good reason, as this plot shows the maximum expected value across all the six mitigation techniques for the Schedule risk Root Cause 1. In general, the maximum expected utility plot will always appear more volatile, since it is capturing the change in the decimal-valued utility as opposed to the integer-valued mitigation technique. The variability in both figures is due to the slight change in the user's preference system, the gamma and k parameters, during the sensitivity analysis. The more variability in these plots, the more the root cause is susceptible to changes in mitigation technique choice. Some root cause mitigation technique output plots show a smooth plane, indicating that throughout the sensitivity analysis the mitigation technique choice did not change, as is the case with the Cost risk output. However, for this example, the Schedule risk volatility is shown. The purpose of examining the sensitivity output is purely for the user's benefit. By examining how the smallest variation in their preference system can affect the choice of mitigation technique, the user will hopefully be more accurate in their data assessment, or, at the very least, they will understand why their decision has changed if their preference information has changed.

Interestingly, the Personnel (PER) risk had less variability in both chosen mitigation technique and maximum expected utility value than the Schedule root causes listed in Table 6.5. This is most likely due to the combination of input parameters and probabilities, since the sensitivity analysis tests different values of the utility gamma parameter and methods of combining these attribute utility functions (k values). Little variation simply indicates that the PER root cause will consistently be one of the best choices of root causes to mitigate.

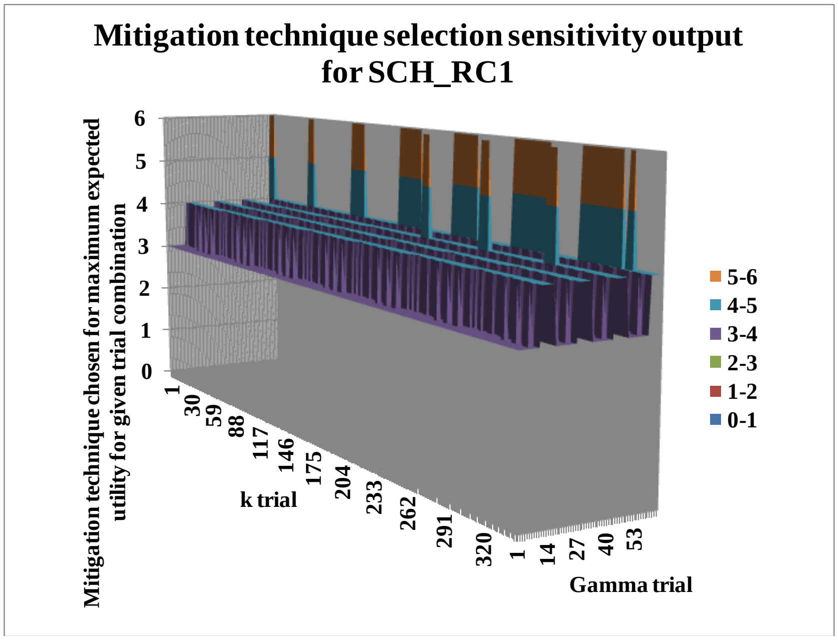

Figure 6.10 - SCH RC1 Mitigation Technique sensitivity output for ARMADILLO case study.

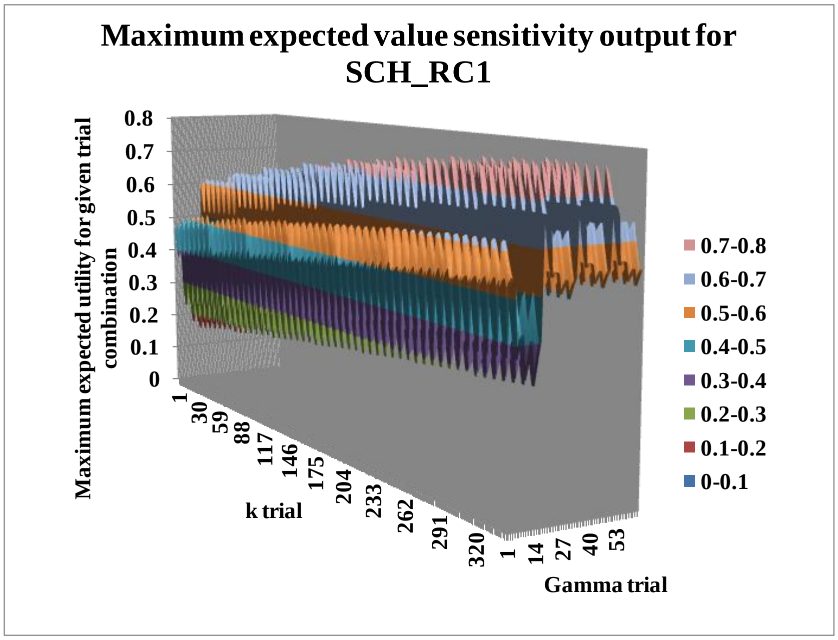

Figure 6.11 - SCH RC1 maximum expected utility output for sensitivity analysis on ARMADILLO case study.

6.4.2 Life-cycle Case Studies

The goal of this set of test cases is to examine the life-cycle of a spacecraft mission and the types of inputs a mission may consider when using the Decision Advisor tool. For these cases, the inputs are based on the ARMADILLO case study, but values are changed to represent extreme examples, e.g. running out of money or time, in order to test the ability of the tool to assess appropriate mitigation technique responses. All test case input values are available in the appendices; unless otherwise noted, the highlighted values represent the values changed from the ARMADILLO case study. For the purposes of this case study analysis, the ARMADILLO mission is assumed to be in the early integration phase.

Development Phase

Assume that when the spacecraft is in development, the probabilities that mitigation techniques are going to fully work are much lower, while the probabilities that the technique either partially works or does not work at all are higher than the ARMADILLO integration phase data. Also, assume that the cost, people, and time necessary for mitigation technique implementation are a lot higher. This is deemed appropriate because learning how to interface, test, and fix issues with a system may take longer when the system is in the initial life-cycle phases as opposed to later in the life-cycle when the user learns the intricacies of the system.

Assume the maximum values are the same: $60,000 for cost, 180 days for time, and 30 people. But because it is the beginning of the spacecraft life-cycle, assume a higher risk tolerance. That is, the user is willing to sacrifice some of the attribute value for a higher chance at the best outcome. So, the utility curve gamma parameters will change to the lowest value parameter. Suppose also that because the spacecraft is in the beginning of its life-cycle, the mission views each individual attribute at their best while the other attributes are at the worst in the same manner: the k_1, k_2, and k_3 values are equal. Assume these attribute preferences are all set to 0.7, meaning that each attribute being at its best while the others are at their worst is equivalent to 70% of the best case scenario. For these reasons, the probabilities, attribute and utility inputs have changed to those in Appendix B. Note that not all values needed to change; those that did change are highlighted for easy identification.

After supplying the values in Appendix B, the top five overall root causes to mitigate are listed in Table 6.6. It is interesting how the four COST root causes are the top four root causes to mitigate, and that the suggested technique is to include contingency in the budget. This outcome makes sense for a mission in the development phase, as many of the components have not yet been purchased. Including budget contingency is perhaps one of the easiest ways to avoid cost overruns, especially for small satellite missions. Also interestingly is the suggested technique of maintaining relationships with vendors. Within the small satellite community, most satellite builders have personal relationships with vendors. These relationships can be valuable in the case that, as this analysis points out, mission funding is delayed. By having a solid relationship with the vendor, missions may be able to delay an invoice, or even negotiate a price to a more acceptable value. Maintaining good relationships with the vendors has helped mitigate cost risk in the Texas Spacecraft Laboratory on more than one occasion. Finally, inadequate documentation was identified as an easy-to-fix root cause in the development phase. This makes sense because at the beginning phases, many missions are still developing their documentation standards. But, according to this analysis, a mission need only build extra margin into their schedule milestones to avoid a schedule slip due to documentation issues.

Table 6.6 - Development phase results.

Root Cause	**Description**	**MT description**	**Expected Utility**	**Rank**
COST / RC2	COTS component price increases	M3 / Include contingency in budget	0.9266	1
COST / RC1	Incomplete understanding	M3 / Include contingency in budget	0.9192	2
COST / RC4	Delay of receiving promised funding	M2 / maintain relationships with vendors	0.9079	3
COST / RC3	Inability to obtain new funding	M3 / Include contingency in budget	0.8968	4
SCH / RC5	Delay due to inadequate documentation	M4 / Build margin into schedule milestones	0.8917	5

Integration Phase

The original ARMADILLO case study represents a mission which is at the beginning of its integration life-cycle phase. All the same inputs will be used as the ARMADILLO case study for this test case, with the exception of the preference information. Assume that less risk is tolerated now that the mission is passed initial development and is in the integration phase. This lower risk tolerance makes sense because the mission would not be willing to jeopardize cost, people, or time as much now that it has flight hardware undergoing flight integration. Also assume that the attributes are no longer viewed equally as during the Development phase. Perhaps, now, cost and time are viewed as more important than people. Perhaps there are deadlines and budgets that need to be met. Say the cost and time attributes are viewed equally, and slightly more importantly than people, at 0.8 each. Table 6.7 gives the preference system applied for the integration phase analysis. Note that a k value of zero simply means the trivial solution was the solution most easily found by the Solver routine. With a k value of zero, the k_i values become conventional weights when combining to obtain the joint utility function.

Table 6.7 - Integration phase preference system

	Gamma	**K**	0
Time	0.025	**K1**	0.8
Cost	0.0005	**K2**	0.7
People	0.15	**K3**	0.8

Based on the ARMADILLO case study data and the preference system listed in Table 6.7, the top five overall root causes to mitigate are shown in Table 6.8. It is interesting that moving from the development phase to the integration phase removes two of the Cost root causes seen in Table 6.6. According to this analysis, delay of funding and inability to obtain new funding are now no longer worth mitigating at the integration phase. This makes sense, because at the integration phase, a mission should have purchased a vast majority of the spacecraft components and need money only for testing and operations. At the integration phase, Schedule is now the primary risk to mitigate. The analysis highlights the mitigation technique of allocating more resources to the task needing completion as the technique most useful for mitigating the mechanical design delay root cause. This was seen in the TSL on a number of occasions. The lab needed the mechanical drawings completed within a certain amount of time, and simply put more students on the task. Soon enough, the root cause had been mitigated. Also note that a Personnel root cause has appeared in the integration phase. Specifically, the root cause is “Loss of Hardware”. This particular root cause appearing in the integration phase makes sense, because it is in this phase that all flight hardware arrives and can easily be misplaced or misused without a tracking system such as a certification log.

Table 6.8 - Integration phase results

Root Cause	**Description**	**MT description**	**Expected Utility**	**Rank**
SCH / RC1	Inability to find desired spacecraft components	M6 / allocate more resources to the task needing completion	0.9353	1
SCH / RC2	Mechanical design delays	M6 / allocate more resources to the task needing completion	0.9353	1
COST / RC2	COTS component price increases	M3 / Include contingency in budget	0.9052	3
COST / RC1	Incomplete understanding of the projected total mission cost	M3 / Include contingency in budget	0.8954	4
PER / RC2	Loss of hardware	M4 / have tracking method for hardware (e.g. inventory system, certification logs)	0.8896	5

Testing Phase

Assume that when the spacecraft is in the testing phase, the probabilities that mitigation techniques are going to fully work, partially work, or not work at all are probably the same as in the integration phase. Also, assume that the cost, people, and time necessary for mitigation technique implementation are the same or less than in the integration phase. This is deemed appropriate because the team must have already learned the majority of how to work with the systems to be in the system testing phase.

Assume the maximum values are the same: $60,000 for cost, 180 days for time, and 30 people. But because it is the middle of the spacecraft life-cycle, assume a conservative risk tolerance. That is, since the spacecraft is already built, the mission does not want to jeopardize, nor can they afford, more time, money, or people than absolutely necessary. So, the utility curve gamma parameters will be the highest parameter. Suppose also that because the spacecraft is in the middle of its life-cycle, the mission views cost as slightly more important than people or time. Perhaps the budget is getting tighter, but the schedule is doing alright as compared to the Integration life-cycle. Assume these attribute preferences are 0.8, 0.7, and 0.7, respectively for cost, people, and time. For these reasons, the probabilities, attribute and utility inputs have changed to those in Appendix C. Note that not all values needed to change; those that did change from the integration phase/ARMADILLO case study data are highlighted for easy identification.

Based on the testing phase data and the preference system given in Appendix C, the top five overall root causes to mitigate are shown in Table 6.9. Notice how the results, with the exception of the expected utility values, are identical to the integration phase results of Table 6.8. This makes sense, though, because testing is essentially an extension of the integration phase. Additionally, most of the changes made from the integration phase to the testing phase involved altering attribute and utility parameter values, but not probabilities. Notice that the expected utility for each root cause has decreased, indicating that it is less favorable to mitigate these than during the integration phase.

Table 6.9 - Testing phase results

Root Cause	**Description**	**MT description**	**Expected Utility**	**Rank**
SCH / RC1	Inability to find desired spacecraft components	M6 / allocate more resources to the task needing completion	0.9074	1
SCH / RC2	Mechanical design delays	M6 / allocate more resources to the task needing completion	0.9074	1
COST / RC2	COTS component price increases	M3 / Include contingency in budget	0.837	3
COST / RC1	Incomplete understanding of the projected total mission cost	M1 / document all costs to ensure proper knowledge for future missions	0.8285	4
PER / RC2	Loss of Hardware	M4 / have tracking method for hardware (e.g. inventory system, certification logs)	0.8182	5

Operations Phase

Once the spacecraft has launched and mission operations have begun, then most likely the mission does not have much money remaining and the team values a quick response to problems. Additionally, the team may be extremely risk averse, because they do not want to jeopardize accomplishing the mission objectives. For these reasons, the utility function parameters are assumed to be the largest, and most conservative, values. Because of the lack of money remaining and necessity for a quick response, let the combining parameters be heavier on cost and time. In this test case, it is assumed that the attribute preferences are 0.95, 0.7, and 0.9 for the cost, people, and time attributes.

Money can still be spent to improve risks associated with the ground station or documentation. On the other hand, any mitigation techniques involving hardware changes have been removed from consideration, since hardware changes on the spacecraft can no longer be made. De-scoping or changing components falls into the hardware change category. While hardware changes may be necessary for ground-based testing, the spacecraft can no longer change and it is spacecraft issues that ground-based testing would be meant to fix. Therefore, costs associated with testing are now assumed to be zero, with the exception of ground station related issues. Any testing is still a valid mitigation technique and its probability of success has increased, assuming the mission has a ground-based system to work through any on-orbit issues. With such a system, the team could run similar tests as were run on the spacecraft. By running these tests, the team could determine issues the satellite is facing and how to fix the problems. However, pre- and post-integration functional tests no longer make sense as a mitigation technique when the mission is the operations phase, other than to help identify unusual spacecraft behavior in-orbit by using equipment on the ground. For the purposes of this analysis, the mitigation technique was removed from consideration for the operations phase.

Based on these rationales, the input parameter values have been modified from the testing life-cycle phase, and are available in Appendix D, where the highlighted values indicate those values changed from the testing phase. Note that Schedule risk is no longer a mission risk, since the spacecraft is in the operations phase. In the other risks, any mitigation techniques referencing schedule have also been removed. Time values also may have decreased for the operations phase considering the teams experience on the system at this point in the life-cycle. In reality, the spacecraft would not be allowed on the launch vehicle if the SC3 root cause events occurred. However, for the purposes of this research, the SC3 mission risk is still analyzed after removing any mitigation techniques involving hardware changes.

Based on the operations phase data and the preference system given in Appendix D, the top five overall root causes to mitigate are shown in Table 6.10. Notice that the

Schedule risk does not appear and recall that the data was removed from consideration, since the spacecraft is now in operations and will not experience a schedule slip. Intriguingly, additional Personnel root causes have replaced the Schedule root causes seen in the previous phases. This makes sense, since the operations phase relies heavily upon team participation for collecting and analyzing the spacecraft data. Table 6.10 shows the easiest root causes to mitigate have to do with team training and attrition. This is especially true with university missions. Notice that the suggested mitigation technique is to have a group of core students. This technique was applied within the TSL with great success; new members are trained by the core members and the core members maintain a level of continuous work through school breaks and graduations.

Table 6.10 - Operations phase results.

Root Cause	**Description**	**MT description**	**Expected Utility**	**Rank**
PER / RC3	Lack of sufficient training for team members	M1 / have group of core (paid) staff/students to ensure things get done on time, provide continuity and leadership	0.8681	1
PER / RC4	Attrition or turnover of team members	M1 / have group of core (paid) staff/students to ensure things get done on time, provide continuity and leadership	0.8681	1
COST / RC2	COTS component price increases	M3 / Include contingency in budget	0.8519	3
COST / RC1	Incomplete understanding of the projected total mission cost	M3 / Include contingency in budget	0.8483	4
PER / RC1	Loss of information	M1 / have documentation method for saving/storing work	0.8455	5

Case Study Concluding Remarks

Notice the risks missing from case study results of Table 6.5 through Table 6.10 – the spacecraft and payload risks. For the values input, the Decision Advisor tool found that it was more beneficial to mitigate the root causes associated with the schedule, cost, and personnel risks, than to mitigate those root causes involving spacecraft or ground station hardware. Intuitively, this makes sense, because mission designers are limited in what they can do to protect components against the harshness of space. However, the cost, personnel, and schedule can be mildly controlled.

The purpose of the life-cycle phase analysis was two-fold. First, the analysis was a method of validating that the Decision Advisor tool could handle any phase of a spacecraft mission and respond with results which made sense for that particular phase. Second, the analysis, along with the data in the appendix, serves as another starting point for missions who wish to use the Decision Advisor tool, but may not know where to start.

6.4.3 Small Satellite Community case studies

As of October 2014, the Decision Advisor software tool was released to a small set of mission designers in an effort to gather initial feedback and work through any preliminary errors. The tool was formally released to the general Small Satellite community in January 2015. As of February 2015, six people have filled out a short survey, similar to the one for the CubeSat Risk Analysis tool, to request the Decision Advisor. Users range from the Jet Propulsion Lab to Adler Planetarium, with a few international organizations as well. With each successive release, the community is asked for feedback as well as their inputs and conclusions. The feedback is collected and saved for a possible future revision of the tool. The inputs and resulting conclusions obtained by using the Decision Advisor will be used as additional case studies to show the tool's functionality and usefulness.

Chapter 7: Conclusion

7.1 Summary of Research

Risk management plans improve the likelihood of mission success by identifying potential failures early and planning mitigation methods to circumvent any issues. However, in the aerospace industry to date, risk management plans have typically only been used for larger and more expensive satellites, and have rarely been applied to satellites in the shape of 10 x 10 x 10 centimeter cubes, called CubeSats. Furthermore, existing risk management plans typically require experienced personnel and significant time to run the analysis. The purpose of this research was to develop two risk management software tools which could be used by anyone with any level of experience. Moreover, the tools simply require the user to enter their mission-specific data; the software tools calculate the required analysis.

The CubeSat Risk Analysis tool was developed for the purpose of reducing the subjectivity associated with estimating the likelihood and consequence of spacecraft mission risks. The tool estimates mission risk in terms of input characteristics, such as satellite form factor, mass, and development cycle. Using a historical database of small satellite missions, which was gathered in the course of this research, the software determines the mission risk root causes which are of the highest concern for the given mission. This risk identification is the first step of a risk management process.

The next step is to determine which mitigation techniques will most effectively decrease the likelihood and/or consequence of the risk event. The CubeSat Decision Advisor tool uses components of decision theory such as decision trees, multi-attribute utility theory, and utility elicitation methods to determine the expected utility of a mitigation technique alternative. Based on the user's value preference system, assessment of success probabilities, and resources required for a given mitigation technique, the tool suggests the course of action which will normatively yield the most value for the cost, people, and time resources required.

To ensure ease-of-use for users of all backgrounds and experience levels, the tools were built in a software package most people already have installed, Microsoft Excel. The Risk Analysis tool has already been released, after extensive testing, to the CubeSat community and has been met with enthusiasm. The tool was validated and the insights gleaned were incorporated into the User's Guide. The first version as well as initial validation and testing of the Decision Advisor tool has been completed. The tool has been released to the Small Satellite Community for use, with a request for feedback and case studies to show the tool working.

The goal of this research was to create a set of risk management software tools never before available, and yet easily accessible and usable, for low-cost small satellite missions. The target audience was originally university labs, who could not otherwise afford expensive software packages. However, the interested parties now also include government, corporate, and international organizations. The research has been well received and the tools are currently providing the expected results.

7.2 FUTURE WORK

During development of the two Excel-based software tools, many tasks were assigned to Future Work in an effort to finish an initial version of each tool. These tasks are left to future students of risk management and decision analysis who wish to improve upon these two tools. Future students may also wish to find additional methods of expanding the reach of the tool, such as through instructional websites, videos, as well as partnering with existing programs such as the University Nanosatellite Program to encourage more universities to use these resources.

7.2.1 Future Developments for the CubeSat Risk Analysis Tool

Chapter 4 detailed the trade studies completed as part of testing assumptions made during the development of the Risk Analysis Tool. Future analysis could expand upon these trade studies and investigate additional alternatives for each of the assumptions mentioned in Chapter 4, as well as assumptions not covered. Specifically, it would be beneficial to step through each piece of the data processing and regression algorithms to ensure the assumptions and steps taken are logical and well-founded. Section 3.3.5 explains the Combining Experts algorithm which would be an excellent starting point for a future researcher to start identifying potential areas for additional trade study analysis. Automation of many of the validation analyses would be useful for expanding the trade space.

For the initial development of the software tool, all input and output terms were assumed to be independent. Obviously, this may not be true. Therefore, it would be useful to have some measure of correlation between input terms such as the time in development versus time in functional testing as well as output root cause likelihood and consequence values. For example, the root cause of an antenna not working may influence the root cause of the radio not working, or vice versa. Additionally, experts were assumed to have independent assessments, but this may not be accurate. Identifying a way to correlate experts may be an area of future study.

Many in industry question the use of the 5x5 L-C chart that is a key element of any risk analysis, and was featured prominently in this research. Complaints range from the issue of subjectivity, which this research attempted to address, to the issue of a linear scale on which to judge risk. While many attempts were made, an adequate replacement for the 5x5 was not created. It is suggested that future students of risk management strive to find alternatives to this heavily-used graphic.

Some demographic information, such as launch date, funding situation, team demographics, and mission success, were not included in the initial regression analysis. Future analyses may consider expanding upon the function forms tested to include these additional terms, e.g. risk as a function of time. Additionally, it is suggested to continue collecting data to improve the model. For example, the survey mentioned in Chapter 3 could be required of all CubeSats to participate in ELaNa, the CubeSat Launch Initiative, or other small satellite launch programs. Once this additional data is collected, future versions of the tool could stratify the data into different relevant classes, such as high school, collegiate, and industry missions, to better reflect the risks posed to each institution.

Many of the data processing algorithms were still subjective. In an effort to minimize subjectivity in this analysis, it is suggested to revisit many key algorithms such as the "Likelihood and N/A" algorithm which mapped whether the event occurred and textual answers such as "N/A" to numerical values (see Section 3.3.4).

7.2.2 Future Developments for the CubeSat Decision Advisor Tool

The biggest improvement for the Decision Advisor Tool would be to expand its capabilities for analysis. That is, to find a way for the user to suggest additional, or modify current, root causes or mitigation techniques for analysis. On the decision tree, the root causes and mitigation techniques are listed generically. But in the user interface, where the user enters all their mission-specific data, the mission risk and root cause is explicitly stated. A user could simply ignore the text, and use the tool for a different purpose, or they could modify the VBA code. Additional versions of the tool could allow the user more flexibility to enter their own risk and root cause textual explanations. Future iterations could also allow users to identify the exact number of mitigation techniques they wish to analyze for a given root cause, rather than the definitive six in the current tool. Users may also find flexibility in the number of outcomes useful. That is, not limiting the outcomes to "Fully Works", "Partially Works", and "Does Not Work".

As with the Risk Analysis Tool, all values were assumed to be independent of one another. This may not be the case, since mitigating one root cause may also mitigate a second root cause, or make additional mitigation techniques more or less likely for that second root cause. Future versions of this tool could include a method by which to indicate this correlation. The reason this type of correlation was not implemented in the current version of the tool was because of limitations with Excel. Therefore, it is also suggested to investigate writing an executable file for the software tool in order to hopefully increase the tool capability.

Typical analysis of decision trees may include a value of information. That is, how would the decision change if given additional information. This additional information could be perfect (such as knowing with certainty whether the mitigation technique would work) or imperfect (an expert opinion on whether the mitigation technique would work). Analysts then determine whether the decision would change, and by how much, yielding the value of the information. Future iterations of the Decision Advisor Tool may consider adding this functionality.

7.3 CONCLUDING REMARKS

Two new Excel-based software tools have been validated and are ready for small satellite mission designers to use in tandem in an effort to increase the likelihood of mission success for low-cost small satellite missions. The Risk Analysis Tool offers a statistical method to identify and analyze the mission risks of highest concern. The Decision Advisor tool allows users to determine how they can best mitigate these risks. Before now, access to such software tools has been deemed proprietary or would cost missions an extraordinary amount of money and time to implement.

This research initiated the use of regression equations to map demographic information to risk likelihood and consequence values. It is hoped that this approach is updated with new data, expanded upon in the function forms tested, and continuously improved to provide the most useful tool possible for small satellite mission designers to help them identify and quantify their risks based on mathematical analysis rather than subjective assessment. The research also established the inaugural use, to the author's knowledge, of decision and multi-attribute utility theories to the problem of small satellite risk management. As with the Risk Analysis tool and the regression equations, additional research could be done to enhance the Decision Advisor tool and make the tool more rigorous in its techniques. It is sincerely hoped that improved versions of the Decision Advisor tool will be developed and released to the small satellite community.

The beneficiaries of this research are numerous. While the initial goal was to provide universities with free software tools to help them develop successful satellite missions, the methods employed are also useful to non-academic institutions such as government agencies and corporations. Additionally, the techniques are applicable across disciplines outside of the small satellite realm. Many programmers, chip designers, and ground station developers are interested in the Decision Advisor tool developed during this research and in learning how to use it for their own purposes.

The goals of this research were met in the development of two easily-accessible and free risk management software tools to assist in university satellite mission development. But more importantly, these tools will reach beyond the academic setting and allow small satellites to continue to evolve as a low-cost platform to accomplish educational, scientific, and military objectives.

Appendix A: ARMADILLO Case Study Data

SCHEDULE RISK

	Root Cause 1			***Root Cause 2***			***Root Cause 3***		
	MT 1	*Choice 1*		**MT 1**	*Choice 1*		**MT 1**	*Choice 1*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.4*	*0.5*	*0.5*	*0.3*	*0.2*	*0.5*	*0.3*	*0.2*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*4*	*6*	*2*	*4*	*6*	*2*	*4*	*6*
Time (days)	*5*	*7*	*10*	*5*	*7*	*10*	*5*	*7*	*10*
	MT 2	*Choice 2*		**MT 2**	*Choice 2*		**MT 2**	*Choice 2*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.4*	*0.5*	*0.2*	*0.3*	*0.5*	*0.4*	*0.4*	*0.2*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
People	*1*	*2*	*10*	*1*	*2*	*10*	*2*	*4*	*10*
Time (days)	*5*	*7*	*10*	*5*	*7*	*10*	*2*	*15*	*30*
	MT 3	*Choice 3*		**MT 3**	*Choice 3*		**MT 3**	*Choice 3*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.3*	*0.6*	*0.1*	*0.3*	*0.6*	*0.25*	*0.5*	*0.25*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
People	*4*	*10*	*20*	*4*	*10*	*20*	*4*	*10*	*20*
Time (days)	*5*	*7*	*10*	*5*	*7*	*10*	*5*	*30*	*90*
	MT 4	*Choice 4*		**MT 4**	*Choice 4*		**MT 4**	*Choice 4*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.6*	*0.3*	*0.1*	*0.3*	*0.6*	*0.1*	*0.3*	*0.6*	*0.1*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*4*	*6*	*1*	*2*	*4*	*1*	*2*	*4*
Time (days)	*5*	*7*	*10*	*5*	*7*	*10*	*5*	*15*	*30*
	MT 5	*Choice 5*		**MT 5**	*Choice 5*		**MT 5**	*Choice 5*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.4*	*0.5*	*0.2*	*0.5*	*0.3*	*0.1*	*0.2*	*0.7*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
People	*5*	*10*	*15*	*5*	*10*	*15*	*5*	*10*	*15*
Time (days)	*5*	*10*	*15*	*5*	*10*	*15*	*5*	*10*	*15*
	MT 6	*Choice 6*		**MT 6**	*Choice 6*		**MT 6**	*Choice 6*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.8*	*0.15*	*0.05*	*0.8*	*0.15*	*0.05*	*0.8*	*0.15*	*0.05*
Cost ($)	*0*	*500*	*1000*	*0*	*500*	*1000*	*0*	*500*	*1000*
People	*0*	*5*	*10*	*0*	*5*	*10*	*2*	*5*	*10*
Time (days)	*0*	*5*	*10*	*0*	*5*	*10*	*2*	*5*	*10*

	Root Cause 4			***Root Cause 5***		
	MT 1	*Choice 1*		**MT 1**	*Choice 1*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.5*	*0.3*	*0.2*	*0.5*	*0.3*	*0.2*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*4*	*6*	*2*	*4*	*6*
Time (days)	*5*	*7*	*10*	*5*	*7*	*14*
	MT 1	*Choice 2*		**MT 2**	*Choice 2*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.2*	*0.4*	*0.4*	*0.4*	*0.4*	*0.2*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*4*	*10*	*2*	*4*	*10*
Time (days)	*2*	*15*	*30*	*2*	*7*	*14*
	MT 3	*Choice 3*		**MT 3**	*Choice 3*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.7*	*0.25*	*0.05*	*0.3*	*0.6*	*0.1*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*4*	*10*	*20*	*4*	*10*	*20*
Time (days)	*5*	*30*	*90*	*5*	*15*	*30*
	MT 4	*Choice 4*		**MT 4**	*Choice 4*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.5*	*0.3*	*0.2*	*0.6*	*0.3*	*0.1*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*1*	*2*	*4*	*1*	*2*	*4*
Time (days)	*5*	*15*	*30*	*5*	*15*	*30*
	MT 5	*Choice 5*		**MT 5**	*Choice 5*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.2*	*0.7*	*0.8*	*0.15*	*0.05*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*5*	*10*	*15*	*5*	*10*	*15*
Time (days)	*5*	*10*	*15*	*5*	*10*	*15*
	MT 6	*Choice 6*		**MT 6**	*Choice 6*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.8*	*0.15*	*0.05*	*0.7*	*0.2*	*0.1*
Cost ($)	*0*	*500*	*1000*	*0*	*0*	*0*
People	*2*	*5*	*10*	*2*	*5*	*10*
Time (days)	*2*	*5*	*10*	*2*	*5*	*10*

PAYLOAD RISK

	Root Cause 1			*Root Cause 2*		
	MT 1	*Choice 1*		**MT 1**	*Choice 1*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.3*	*0.6*	*0.1*	*0.3*	*0.6*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*4*	*10*	*20*	*4*	*10*	*20*
Time (days)	*5*	*7*	*10*	*5*	*7*	*10*
	MT 2	*Choice 2*		**MT 2**	*Choice 2*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.3*	*0.6*	*0.1*	*0.3*	*0.6*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*4*	*6*	*2*	*4*	*6*
Time (days)	*5*	*7*	*10*	*5*	*7*	*10*
	MT 3	*Choice 3*		**MT 3**	*Choice 3*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.4*	*0.4*	*0.2*	*0.8*	*0.15*	*0.05*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*4*	*8*	*12*	*4*	*8*	*12*
Time (days)	*10*	*30*	*45*	*10*	*30*	*45*
	MT 4	*Choice 4*		**MT 4**	*Choice 4*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.7*	*0.2*	*0.1*	*0.85*	*0.1*	*0.05*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*4*	*8*	*12*	*4*	*8*	*12*
Time (days)	*10*	*30*	*45*	*10*	*30*	*45*
	MT 5	*Choice 5*		**MT 5**	*Choice 5*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.7*	*0.2*	*0.1*	*0.1*	*0.3*	*0.6*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*4*	*8*	*12*	*4*	*8*	*12*
Time (days)	*10*	*30*	*45*	*10*	*30*	*45*

	Root Cause 3			***Root Cause 4***		
	MT 1	*Choice 1*		**MT 1**	*Choice 1*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.3*	*0.6*	*0.1*	*0.3*	*0.6*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*4*	*10*	*20*	*4*	*10*	*20*
Time (days)	*5*	*7*	*10*	*5*	*7*	*10*
	MT 2	*Choice 1*		**MT 2**	*Choice 2*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.3*	*0.6*	*0.1*	*0.3*	*0.6*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*4*	*6*	*2*	*4*	*6*
Time (days)	*5*	*7*	*10*	*5*	*7*	*10*
	MT 3	*Choice 3*		**MT 3**	*Choice 2*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.3*	*0.4*	*0.3*	*0.3*	*0.4*	*0.3*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*4*	*8*	*12*	*4*	*8*	*12*
Time (days)	*10*	*30*	*45*	*10*	*30*	*45*
	MT 4	*Choice 4*		**MT 4**	*Choice 4*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.3*	*0.4*	*0.3*	*0.3*	*0.4*	*0.3*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*4*	*8*	*12*	*4*	*8*	*12*
Time (days)	*10*	*30*	*45*	*10*	*30*	*45*
	MT 5	*Choice 5*		**MT 5**	*Choice 5*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.85*	*0.1*	*0.05*	*0.85*	*0.1*	*0.05*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*4*	*8*	*12*	*4*	*8*	*12*
Time (days)	*10*	*30*	*45*	*10*	*30*	*45*

SC1 RISK

	Root Cause 1			***Root Cause 2***			***Root Cause 3***		
	MT 1	*Choice 1*		**MT 1**	*Choice 1*		**MT 1**	*Choice 1*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.2*	*0.2*	*0.6*	*0.4*	*0.5*	*0.1*	*0.4*	*0.5*	*0.1*
Cost ($)	*5000*	*7500*	*10000*	*2500*	*5000*	*7500*	*2500*	*5000*	*7500*
People	*4*	*6*	*10*	*2*	*4*	*6*	*2*	*4*	*6*
Time (days)	*30*	*60*	*90*	*10*	*20*	*30*	*10*	*20*	*30*
	MT 2	*Choice 7*		**MT 2**	*Choice 3*		**MT 2**	*Choice 3*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.85*	*0.1*	*0.05*	*0.65*	*0.25*	*0.1*	*0.8*	*0.1*	*0.1*
Cost ($)	*0*	*5000*	*7500*	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*4*	*8*	*4*	*6*	*10*	*4*	*6*	*10*
Time (days)	*15*	*30*	*60*	*5*	*10*	*15*	*5*	*10*	*15*
				MT 3	*Choice 4*		**MT 3**	*Choice 4*	
				Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability				*0.7*	*0.2*	*0.1*	*0.7*	*0.2*	*0.1*
Cost ($)				*0*	*0*	*0*	*0*	*0*	*0*
People				*4*	*6*	*10*	*4*	*6*	*10*
Time (days)				*5*	*10*	*15*	*5*	*10*	*15*
				MT 4	*Choice 5*		**MT 4**	*Choice 5*	
				Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability				*0.8*	*0.1*	*0.1*	*0.65*	*0.25*	*0.1*
Cost ($)				*0*	*0*	*0*	*0*	*0*	*0*
People				*4*	*6*	*10*	*4*	*6*	*10*
Time (days)				*5*	*10*	*15*	*5*	*10*	*15*
				MT 5	*Choice 6*		**MT 5**	*Choice 6*	
				Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability				*0.8*	*0.1*	*0.1*	*0.8*	*0.1*	*0.1*
Cost ($)				*0*	*0*	*0*	*0*	*0*	*0*
People				*2*	*4*	*6*	*2*	*4*	*6*
Time (days)				*10*	*15*	*20*	*10*	*15*	*20*
				MT 6	*Choice 8*		**MT 6**	*Choice 8*	
				Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability				*0.6*	*0.3*	*0.1*	*0.7*	*0.2*	*0.1*
Cost ($)				*0*	*0*	*0*	*0*	*0*	*0*
People				*2*	*4*	*6*	*2*	*4*	*6*
Time (days)				*10*	*15*	*20*	*10*	*15*	*20*

	Root Cause 4			***Root Cause 5***		
	MT 1	*Choice 1*		**MT 1**	*Choice 1*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.6*	*0.3*	*0.1*	*0.6*	*0.3*	*0.1*
Cost ($)	*5000*	*7500*	*10000*	*2500*	*5000*	*7500*
People	*4*	*6*	*10*	*4*	*6*	*10*
Time (days)	*30*	*45*	*60*	*10*	*15*	*30*
	MT 2	*Choice 3*		**MT 2**	*Choice 3*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.65*	*0.25*	*0.1*	*0.75*	*0.15*	*0.1*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*4*	*6*	*10*	*4*	*6*	*10*
Time (days)	*5*	*10*	*15*	*5*	*10*	*15*
	MT 3	*Choice 4*		**MT 3**	*Choice 4*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.7*	*0.2*	*0.1*	*0.7*	*0.2*	*0.1*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*4*	*6*	*10*	*4*	*6*	*10*
Time (days)	*5*	*10*	*15*	*5*	*10*	*15*
	MT 4	*Choice 5*		**MT 4**	*Choice 5*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.8*	*0.1*	*0.1*	*0.8*	*0.1*	*0.1*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*4*	*6*	*10*	*4*	*6*	*10*
Time (days)	*5*	*10*	*15*	*5*	*10*	*15*
	MT 5	*Choice 6*		**MT 5**	*Choice 6*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.8*	*0.1*	*0.1*	*0.8*	*0.1*	*0.1*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*4*	*6*	*2*	*4*	*6*
Time (days)	*10*	*15*	*20*	*10*	*15*	*20*
	MT 6	*Choice 8*		**MT 6**	*Choice 8*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.8*	*0.1*	*0.1*	*0.65*	*0.25*	*0.1*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*4*	*6*	*2*	*4*	*6*
Time (days)	*10*	*15*	*20*	*10*	*15*	*20*

SC2 RISK

	Root Cause 1			***Root Cause 2***			***Root Cause 3***		
	MT 1	*Choice 1*		**MT 1**	*Choice 1*		**MT 1**	*Choice 1*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.6*	*0.3*	*0.1*	*0.6*	*0.3*	*0.1*	*0.6*	*0.3*	*0.1*
Cost ($)	*0*	*500*	*1000*	*0*	*12000*	*24000*	*0*	*20000*	*60000*
People	*2*	*4*	*6*	*2*	*4*	*6*	*2*	*4*	*6*
Time (days)	*5*	*10*	*15*	*5*	*30*	*60*	*5*	*60*	*180*
	MT 2	*Choice 2*		**MT 2**	*Choice 2*		**MT 2**	*Choice 2*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.7*	*0.2*	*0.1*	*0.7*	*0.2*	*0.1*	*0.7*	*0.2*	*0.1*
Cost ($)	*0*	*500*	*1000*	*0*	*12000*	*24000*	*0*	*20000*	*60000*
People	*4*	*8*	*10*	*4*	*8*	*10*	*4*	*8*	*10*
Time (days)	*10*	*20*	*30*	*10*	*30*	*60*	*10*	*60*	*180*
	MT 3	*Choice 3*		**MT 3**	*Choice 3*		**MT 3**	*Choice 3*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.8*	*0.1*	*0.1*	*0.8*	*0.1*	*0.1*	*0.8*	*0.1*	*0.1*
Cost ($)	*0*	*500*	*1000*	*0*	*12000*	*24000*	*0*	*20000*	*60000*
People	*6*	*12*	*15*	*6*	*12*	*15*	*6*	*12*	*15*
Time (days)	*14*	*30*	*45*	*15*	*30*	*60*	*15*	*60*	*180*
	MT 4	*Choice 6*		**MT 4**	*Choice 7*		**MT 4**	*Choice 7*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.8*	*0.1*	*0.1*	*0.8*	*0.1*	*0.1*	*0.8*	*0.1*	*0.1*
Cost ($)	*0*	*500*	*1000*	*0*	*12000*	*24000*	*0*	*20000*	*60000*
People	*4*	*8*	*10*	*4*	*8*	*10*	*4*	*8*	*10*
Time (days)	*10*	*20*	*30*	*15*	*30*	*60*	*15*	*60*	*180*
	MT 5	*Choice 7*		**MT 5**	*Choice 8*		**MT 5**	*Choice 8*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.8*	*0.1*	*0.1*	*0.7*	*0.2*	*0.1*	*0.7*	*0.2*	*0.1*
Cost ($)	*0*	*500*	*1000*	*0*	*12000*	*24000*	*0*	*20000*	*60000*
People	*4*	*8*	*10*	*2*	*4*	*6*	*2*	*4*	*6*
Time (days)	*10*	*20*	*30*	*5*	*30*	*60*	*5*	*60*	*180*
	MT 6	*Choice 8*		**MT 6**	*Choice 10*		**MT 6**	*Choice 10*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.7*	*0.2*	*0.1*	*0.2*	*0.4*	*0.4*	*0.2*	*0.4*	*0.4*
Cost ($)	*0*	*500*	*1000*	*2000*	*12000*	*24000*	*3000*	*20000*	*60000*
People	*2*	*4*	*6*	*4*	*6*	*10*	*4*	*6*	*10*
Time (days)	*5*	*10*	*15*	*60*	*90*	*180*	*60*	*90*	*180*

	Root Cause 4			***Root Cause 5***		
	MT 1	*Choice 1*		**MT 1**	*Choice 1*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.6*	*0.3*	*0.1*	*0.6*	*0.3*	*0.1*
Cost ($)	*0*	*3500*	*7000*	*0*	*2000*	*9500*
People	*2*	*4*	*6*	*2*	*4*	*6*
Time (days)	*5*	*15*	*42*	*5*	*15*	*90*
	MT 2	*Choice 2*		**MT 2**	*Choice 2*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.7*	*0.2*	*0.1*	*0.7*	*0.2*	*0.1*
Cost ($)	*0*	*3500*	*7000*	*0*	*2000*	*9500*
People	*4*	*8*	*10*	*4*	*8*	*10*
Time (days)	*5*	*15*	*42*	*5*	*15*	*90*
	MT 3	*Choice 3*		**MT 3**	*Choice 3*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.8*	*0.1*	*0.1*	*0.8*	*0.1*	*0.1*
Cost ($)	*0*	*3500*	*7000*	*0*	*2000*	*9500*
People	*6*	*12*	*15*	*6*	*12*	*15*
Time (days)	*5*	*15*	*42*	*5*	*15*	*90*
	MT 4	*Choice 7*		**MT 4**	*Choice 7*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.8*	*0.1*	*0.1*	*0.8*	*0.1*	*0.1*
Cost ($)	*0*	*3500*	*7000*	*0*	*2000*	*9500*
People	*4*	*8*	*10*	*4*	*8*	*10*
Time (days)	*10*	*15*	*42*	*10*	*15*	*90*
	MT 5	*Choice 9*		**MT 5**	*Choice 9*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.8*	*0.1*	*0.1*	*0.8*	*0.1*	*0.1*
Cost ($)	*0*	*3500*	*7000*	*0*	*2000*	*9500*
People	*2*	*4*	*6*	*2*	*4*	*6*
Time (days)	*5*	*15*	*42*	*5*	*15*	*90*
	MT 6	*Choice 10*		**MT 6**	*Choice 10*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.2*	*0.4*	*0.4*	*0.2*	*0.4*	*0.4*
Cost ($)	*3500*	*7000*	*14000*	*2000*	*7500*	*9500*
People	*4*	*6*	*10*	*4*	*6*	*10*
Time (days)	*60*	*90*	*180*	*15*	*90*	*90*

	Root Cause 6			***Root Cause 7***		
	MT 1	*Choice 7*		**MT 1**	*Choice 12*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.65*	*0.25*	*0.1*	*0.8*	*0.1*	*0.1*
Cost ($)	*0*	*500*	*1000*	*0*	*500*	*1000*
People	*4*	*8*	*10*	*8*	*16*	*24*
Time (days)	*5*	*15*	*30*	*10*	*30*	*60*
	MT 2	*Choice 12*		**MT 2**	*Choice 14*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.8*	*0.1*	*0.1*	*0.75*	*0.15*	*0.1*
Cost ($)	*0*	*500*	*1000*	*0*	*500*	*1000*
People	*8*	*16*	*24*	*4*	*8*	*10*
Time (days)	*10*	*30*	*60*	*10*	*30*	*60*
	MT 3	*Choice 13*		**MT 3**	*Choice 16*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.75*	*0.15*	*0.1*	*0.7*	*0.2*	*0.1*
Cost ($)	*0*	*500*	*1000*	*0*	*500*	*1000*
People	*4*	*8*	*10*	*4*	*6*	*8*
Time (days)	*10*	*30*	*60*	*30*	*60*	*90*
	MT 4	*Choice 15*				
	Fully	**Partially**	**Doesn't**			
Probability	*0.7*	*0.2*	*0.1*			
Cost ($)	*0*	*500*	*1000*			
People	*4*	*6*	*8*			
Time (days)	*30*	*60*	*90*			
	MT 5	*Choice 3*				
	Fully	**Partially**	**Doesn't**			
Probability	*0.65*	*0.25*	*0.1*			
Cost ($)	*0*	*500*	*1000*			
People	*2*	*4*	*8*			
Time (days)	*10*	*15*	*30*			

SC3 RISK

	Root Cause 1			***Root Cause 2***		
	MT 1	*Choice 1*		**MT 1**	*Choice 1*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.8*	*0.1*	*0.1*	*0.8*	*0.1*	*0.1*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*4*	*6*	*10*	*4*	*6*	*10*
Time (days)	*30*	*60*	*90*	*30*	*60*	*90*
	MT 2	*Alternate #1*		**MT 2**	*Choice 2*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.6*	*0.3*	*0.1*	*0.75*	*0.15*	*0.1*
Cost ($)	*500*	*1000*	*1500*	*200*	*400*	*600*
People	*6*	*10*	*15*	*2*	*4*	*6*
Time (days)	*60*	*90*	*120*	*10*	*20*	*30*
				MT 3	*Choice 3*	
				Fully	**Partially**	**Doesn't**
				0.65	*0.25*	*0.1*
				500	*1500*	*3000*
				2	*4*	*6*
				10	*20*	*30*
				MT 4	*Choice 6*	
				Fully	**Partially**	**Doesn't**
				0.8	*0.1*	*0.1*
				0	*0*	*0*
				10	*20*	*30*
				2	*5*	*10*

	Root Cause 3			***Root Cause 4***		
	MT 1	*Choice 4*		**MT 1**	*Choice 1*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.7*	*0.2*	*0.1*	*0.7*	*0.2*	*0.1*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*4*	*6*	*4*	*6*	*10*
Time (days)	*10*	*20*	*30*	*30*	*60*	*90*
	MT 2	*Choice 5*		**MT 2**	*Choice 6*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.8*	*0.1*	*0.1*	*0.8*	*0.1*	*0.1*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*6*	*8*	*10*	*10*	*20*	*30*
Time (days)	*15*	*30*	*45*	*2*	*5*	*10*
	MT 3	*Choice 6*				
	Fully	**Partially**	**Doesn't**			
Probability	*0.6*	*0.2*	*0.2*			
Cost ($)	*0*	*0*	*0*			
People	*10*	*20*	*30*			
Time (days)	*2*	*5*	*10*			

PER RISK

	Root Cause 1			Root Cause 2			Root Cause 3		
	MT 1	*Choice 3*		**MT 1**	*Choice 1*		**MT 1**	*Choice 1*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.8*	*0.1*	*0.1*	*0.4*	*0.4*	*0.2*	*0.8*	*0.15*	*0.05*
Cost ($)	*0*	*0*	*0*	*20000*	*40000*	*60000*	*20000*	*40000*	*60000*
People	*2*	*4*	*6*	*1*	*5*	*10*	*1*	*5*	*10*
Time (days)	*4*	*10*	*15*	*0*	*15*	*30*	*0*	*15*	*30*
	MT 2	*Choice 4*		**MT 2**	*Choice 6*		**MT 2**	*Choice 2*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.5*	*0.3*	*0.2*	*0.9*	*0.05*	*0.05*	*0.8*	*0.15*	*0.05*
Cost ($)	*0*	*0*	*0*	*0*	*1000*	*5000*	*0*	*0*	*0*
People	*3*	*9*	*12*	*2*	*4*	*6*	*3*	*6*	*9*
Time (days)	*10*	*30*	*45*	*1*	*5*	*10*	*1*	*5*	*10*
	MT 3	*Choice 5*		**MT 3**	*Choice 7*		**MT 3**	*Choice 4*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.3*	*0.4*	*0.3*	*0.6*	*0.2*	*0.2*	*0.5*	*0.3*	*0.2*
Cost ($)	*0*	*0*	*0*	*0*	*1000*	*5000*	*0*	*0*	*0*
People	*2*	*4*	*6*	*2*	*4*	*6*	*3*	*9*	*12*
Time (days)	*2*	*5*	*10*	*1*	*5*	*10*	*10*	*30*	*45*
	MT 4	*Choice 10*		**MT 4**	*Choice 11*		**MT 4**	*Choice 10*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.3*	*0.4*	*0.3*	*0.8*	*0.15*	*0.05*	*0.85*	*0.1*	*0.05*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
People	*3*	*9*	*12*	*2*	*4*	*6*	*3*	*6*	*9*
Time (days)	*10*	*30*	*45*	*1*	*5*	*10*	*2*	*30*	*45*

	Root Cause 4			***Root Cause 5***		
	MT 1	*Choice 1*		**MT 1**	*Choice 1*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.8*	*0.15*	*0.05*	*0.7*	*0.15*	*0.15*
Cost ($)	*20000*	*40000*	*60000*	*20000*	*40000*	*60000*
People	*1*	*5*	*10*	*1*	*5*	*10*
Time (days)	*0*	*15*	*30*	*0*	*15*	*30*
	MT 2	*Choice 3*		**MT 2**	*Choice 3*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.6*	*0.3*	*0.1*	*0.6*	*0.3*	*0.1*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*4*	*6*	*2*	*4*	*6*
Time (days)	*4*	*10*	*15*	*4*	*10*	*15*
	MT 3	*Choice 4*		**MT 3**	*Choice 4*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.7*	*0.2*	*0.1*	*0.85*	*0.1*	*0.05*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*3*	*9*	*12*	*3*	*9*	*12*
Time (days)	*10*	*30*	*45*	*10*	*30*	*45*
	MT 4	*Choice 7*		**MT 4**	*Choice 7*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.6*	*0.2*	*0.2*	*0.5*	*0.3*	*0.2*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*4*	*6*	*2*	*4*	*6*
Time (days)	*1*	*5*	*10*	*1*	*5*	*10*
	MT 5	*Choice 8*		**MT 5**	*Choice 8*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.7*	*0.2*	*0.1*	*0.5*	*0.3*	*0.2*
Cost ($)	*50*	*100*	*200*	*50*	*100*	*200*
People	*2*	*4*	*6*	*2*	*4*	*6*
Time (days)	*1*	*4*	*5*	*1*	*4*	*5*
	MT 6	*Alternate #1*		**MT 6**	*Choice 9*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.6*	*0.2*	*0.2*	*0.8*	*0.1*	*0.1*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*4*	*6*	*10*	*3*	*9*	*12*
Time (days)	*10*	*30*	*45*	*10*	*30*	*45*

COST RISK

	Root Cause 1			*Root Cause 2*		
	MT 1	*Choice 1*		**MT 1**	*Choice 1*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.9*	*0.05*	*0.05*	*0.2*	*0.2*	*0.6*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*4*	*6*	*2*	*4*	*6*
Time (days)	*2*	*5*	*10*	*2*	*5*	*10*
	MT 2	*Choice 2*		**MT 2**	*Choice 2*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.7*	*0.2*	*0.1*	*0.8*	*0.05*	*0.15*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*4*	*6*	*2*	*4*	*6*
Time (days)	*1*	*2*	*4*	*1*	*2*	*4*
	MT 3	*Choice 3*		**MT 3**	*Choice 3*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.8*	*0.15*	*0.05*	*0.9*	*0.1*	*0*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*4*	*6*	*2*	*4*	*6*
Time (days)	*1*	*2*	*4*	*1*	*2*	*4*
	MT 4	*Choice 4*		**MT 4**	*Choice 4*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.3*	*0.6*	*0.1*	*0.4*	*0.2*	*0.4*
Cost ($)	*100*	*200*	*500*	*100*	*200*	*500*
People	*4*	*8*	*12*	*4*	*8*	*12*
Time (days)	*5*	*15*	*30*	*5*	*15*	*30*
	MT 5	*Choice 5*		**MT 5**	*Choice 5*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.5*	*0.3*	*0.2*	*0.7*	*0.2*	*0.1*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*4*	*8*	*12*	*4*	*8*	*12*
Time (days)	*5*	*15*	*30*	*5*	*15*	*30*
	MT 6	*Choice 6*		**MT 6**	*Choice 6*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.6*	*0.2*	*0.2*	*0.8*	*0.1*	*0.1*
Cost ($)	*1000*	*5000*	*10000*	*1000*	*5000*	*10000*
People	*4*	*8*	*12*	*4*	*8*	*12*
Time (days)	*15*	*30*	*45*	*15*	*30*	*45*

	Root Cause 3			*Root Cause 4*		
	MT 1	*Choice 1*		**MT 1**	*Choice 1*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.2*	*0.2*	*0.6*	*0.2*	*0.2*	*0.6*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*4*	*6*	*2*	*4*	*6*
Time (days)	*2*	*5*	*10*	*2*	*5*	*10*
	MT 2	*Choice 2*		**MT 2**	*Choice 2*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.2*	*0.2*	*0.6*	*0.2*	*0.2*	*0.6*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*4*	*6*	*2*	*4*	*6*
Time (days)	*1*	*2*	*4*	*1*	*2*	*4*
	MT 3	*Choice 3*		**MT 3**	*Choice 3*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.1*	*0.8*	*0.1*	*0.1*	*0.8*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*4*	*6*	*2*	*4*	*6*
Time (days)	*1*	*2*	*4*	*1*	*2*	*4*
	MT 4	*Choice 4*		**MT 4**	*Choice 4*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.8*	*0.1*	*0.1*	*0.3*	*0.3*	*0.4*
Cost ($)	*100*	*200*	*500*	*100*	*200*	*500*
People	*4*	*8*	*12*	*4*	*8*	*12*
Time (days)	*5*	*15*	*30*	*5*	*15*	*30*
	MT 5	*Choice 5*		**MT 5**	*Choice 5*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.1*	*0.8*	*0.3*	*0.3*	*0.4*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*4*	*8*	*12*	*4*	*8*	*12*
Time (days)	*5*	*15*	*30*	*5*	*15*	*30*
	MT 6	*Choice 6*		**MT 6**	*Choice 6*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.7*	*0.2*	*0.1*	*0.7*	*0.2*	*0.1*
Cost ($)	*1000*	*5000*	*10000*	*1000*	*5000*	*10000*
People	*4*	*8*	*12*	*4*	*8*	*12*
Time (days)	*15*	*30*	*45*	*15*	*30*	*45*

TIME PREFERENCE

For completing the Time Preference GUI, we use the following for the ARMADILLO mission, in the order they are displayed:

1. A maximum of 180 days (which aligns with the maximum value entered during entering of risk information)

2. A decrease of 75 days implementation time is worth the increased risk of the worst scenario – “23 days” is chosen.

3. Fewer days implementation time and a higher likelihood of the best scenario is preferred – “27 days” is chosen.

4. A decrease of 40 days implementation time is worth the increased risk of the worst scenario – “14 days” is chosen.

5. Fewer days implementation time and a higher likelihood of the best scenario is preferred – “6 days” is chosen.

6. A decrease of 31 days implementation time is worth the increased risk of the worst scenario – “23 days” is chosen.

7. A decrease of 9 days implementation time is worth the increased risk of the worst scenario – “14 days” is chosen.

8. Fewer days implementation time and a higher likelihood of the best scenario is preferred – “11 days” is chosen.

9. While the worst scenario has a higher likelihood, the implementation time is decreased by 16 days – “7 days” is chosen.

Once these values are entered and the “Save and Exit” option is chosen, the preferences are summarized on the “ucurves” page and should match the values in Table A.1.

Table A.1 - Time preference results from "ucurves" page.

	Max	180			
	Counts	3	2	0	3
	Gammas	0.01	0.025	0.05	0.1
Chosen Time Gamma:		0.1			

COST PREFERENCE

For completing the Cost Preference GUI, we use the following for the ARMADILLO mission, in the order they are displayed:

1. A maximum of $60,000 (which aligns with the maximum value entered during entering of risk information)

2. A decrease of $12,638 implementation cost is worth the increased risk of the worst scenario – "$1151" is chosen.

3. The two values are the same, and so the one with a higher likelihood of the best scenario is chosen.

4. A decrease of $6,214 implementation cost is worth the increased risk of the worst scenario – "$693" is chosen.

5. A decrease of $1,098 implementation cost is worth the increased risk of the worst scenario – "$288" is chosen.

6. A decrease of $1,622 implementation cost is worth the increased risk of the worst scenario – "$1151" is chosen.

7. A decrease of $2,176 implementation cost is worth the increased risk of the worst scenario – "$693" is chosen.

8. The lower cost also coincides with the higher likelihood at the best scenario, so "$575" is chosen.

9. While the worst scenario has a higher likelihood, the implementation cost is decreased by $2,522 – "$347" is chosen.

Once these values are entered and the "Save and Exit" option is chosen, the preferences are summarized on the "ucurves" page and should match the values in Table A.2

Table A.2 - Cost utility preference summary from "ucurves" page.

	Max	60000			
	Counts	3	2	0	3
	Gammas	0.0001	0.0005	0.001	0.002
Chosen Cost Gamma:		0.002			

PEOPLE PREFERENCE

For completing the People Preference GUI, we use the following for the ARMADILLO mission, in the order they are displayed:

1. A maximum of 30 people (which aligns with the maximum value entered during entering of risk information)

2. A decrease of 12 people to implement is worth the increased risk of the worst scenario – "5 people" is chosen.

3. Fewer people to implement and a higher likelihood of the best scenario is preferred – "5 people" is chosen.

4. A decrease of 7 people to implement is worth the increased risk of the worst scenario – "3 people" is chosen.

5. Fewer people to implement and a higher likelihood of the best scenario is preferred – "1 person" is chosen.

6. A decrease of 4 people to implement is worth the increased risk of the worst scenario – "5 people" is chosen.

7. A decrease of 1 person to implement is not worth the increased risk of the worst scenario – "4 people" is chosen.

8. Fewer people to implement and a higher likelihood of the best scenario is preferred – "2 people" is chosen.

9. A decrease of 3 people to implement is not worth the increased risk of the worst scenario – “4 people” is chosen.

Once these values are entered and the “Save and Exit” option is chosen, the preferences are summarized on the “ucurves” page and should match the values in Table A.3

Table A.3 - preference summary from "ucurves" page.

	Max	30			
	Counts	4	1	0	3
	Gammas	0.05	0.15	0.25	0.5
Chosen People Gamma:		0.05			

JOINT PREFERENCE

For completing the Joint Preference GUI, we use the following for the ARMADILLO mission, in the order they are displayed:

1. Assume that cost being at its best while the people and time attributes are at their worst is equivalent to 90% of the best of all three attributes. Perhaps the budget is very tight on this mission, and every dollar matters. For this mission, people and time may be more flexible.

2. Since the number of people used to implement a mitigation technique may be more flexible than the cost for the ARMADILLO mission but less flexible than the amount of time it takes, assume that people at its best while the other two parameters are at their worst is equivalent to 75% the best of all three attributes.

3. For the ARMADILLO mission, time has not been a huge factor, but it will become more important as the mission enters into fabrication and testing. However, people and cost are still the top priorities. So, assume that time at its best while the other

two are at their worst is equivalent to 70% of all the parameters at their best. Because this value is just slightly less than the value for people at the best, we show that people and time are valued almost the same amount.

After selecting “Save and Exit”, a solver routine is automatically run to find the final joint utility function variable. Once the routine is finished, the joint utility parameters should match Table A.4

Table A.4 - Joint utility function parameters.

ksolve	-0.99156
k1	0.9
k2	0.75
k3	0.7

Appendix B: Development Life Cycle Phase Data

Recall that the highlighted values represent values changed from the ARMADILLO case study from Appendix A.

SCHEDULE RISK

	Root Cause 1			***Root Cause 2***			***Root Cause 3***		
	MT 1	*Choice 1*		**MT 1**	*Choice 1*		**MT 1**	*Choice 1*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.4*	*0.5*	*0.2*	*0.5*	*0.3*	*0.2*	*0.5*	*0.3*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*4*	*6*	*2*	*4*	*6*	*2*	*4*	*6*
Time (days)	*10*	*14*	*20*	*10*	*14*	*20*	*10*	*14*	*20*
	MT 2	*Choice 2*		**MT 2**	*Choice 2*		**MT 2**	*Choice 2*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.4*	*0.5*	*0.2*	*0.3*	*0.5*	*0.2*	*0.4*	*0.4*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*4*	*20*	*2*	*4*	*20*	*4*	*8*	*20*
Time (days)	*10*	*14*	*20*	*10*	*14*	*20*	*4*	*30*	*45*
	MT 3	*Choice 3*		**MT 3**	*Choice 3*		**MT 3**	*Choice 3*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.3*	*0.6*	*0.1*	*0.3*	*0.6*	*0.15*	*0.6*	*0.25*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
People	*8*	*20*	*30*	*8*	*20*	*30*	*8*	*15*	*25*
Time (days)	*10*	*14*	*20*	*10*	*14*	*20*	*10*	*45*	*100*
	MT 4	*Choice 4*		**MT 4**	*Choice 4*		**MT 4**	*Choice 4*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.2*	*0.6*	*0.2*	*0.3*	*0.6*	*0.1*	*0.1*	*0.6*	*0.3*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
People	*4*	*8*	*12*	*2*	*4*	*8*	*2*	*4*	*8*
Time (days)	*10*	*14*	*20*	*10*	*14*	*20*	*10*	*30*	*45*
	MT 5	*Choice 5*		**MT 5**	*Choice 5*		**MT 5**	*Choice 5*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.4*	*0.5*	*0.2*	*0.5*	*0.3*	*0.1*	*0.2*	*0.7*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
People	*10*	*20*	*30*	*10*	*20*	*30*	*10*	*20*	*30*
Time (days)	*10*	*20*	*30*	*10*	*20*	*30*	*10*	*20*	*30*
	MT 6	*Choice 6*		**MT 6**	*Choice 6*		**MT 6**	*Choice 6*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.55*	*0.35*	*0.05*	*0.8*	*0.15*	*0.05*	*0.15*	*0.8*
Cost ($)	*500*	*1000*	*1500*	*500*	*1000*	*1500*	*0*	*500*	*1000*
People	*5*	*10*	*15*	*5*	*10*	*15*	*2*	*5*	*10*
Time (days)	*5*	*10*	*15*	*5*	*10*	*15*	*2*	*5*	*10*

	Root Cause 4			***Root Cause 5***		
	MT 1	*Choice 1*		**MT 1**	*Choice 1*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.2*	*0.5*	*0.3*	*0.2*	*0.3*	*0.5*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*4*	*8*	*12*	*2*	*4*	*6*
Time (days)	*10*	*14*	*20*	*5*	*7*	*14*
	MT 1	*Choice 2*		**MT 2**	*Choice 2*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.2*	*0.4*	*0.4*	*0.2*	*0.4*	*0.4*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*4*	*10*	*2*	*4*	*10*
Time (days)	*2*	*15*	*30*	*2*	*7*	*14*
	MT 3	*Choice 3*		**MT 3**	*Choice 3*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.05*	*0.7*	*0.25*	*0.1*	*0.3*	*0.6*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*8*	*20*	*30*	*4*	*10*	*20*
Time (days)	*10*	*45*	*100*	*5*	*15*	*30*
	MT 4	*Choice 4*		**MT 4**	*Choice 4*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.2*	*0.5*	*0.3*	*0.1*	*0.6*	*0.3*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*4*	*8*	*1*	*2*	*4*
Time (days)	*5*	*15*	*30*	*5*	*15*	*30*
	MT 5	*Choice 5*		**MT 5**	*Choice 5*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.2*	*0.7*	*0.05*	*0.8*	*0.15*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*10*	*20*	*30*	*10*	*15*	*20*
Time (days)	*10*	*20*	*30*	*5*	*10*	*15*
	MT 6	*Choice 6*		**MT 6**	*Choice 6*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.05*	*0.15*	*0.8*	*0.1*	*0.2*	*0.7*
Cost ($)	*500*	*1000*	*1500*	*0*	*0*	*0*
People	*4*	*10*	*20*	*4*	*10*	*15*
Time (days)	*4*	*10*	*20*	*8*	*15*	*25*

PAYLOAD RISK

	Root Cause 1			Root Cause 2		
	MT 1	*Choice 1*		**MT 1**	*Choice 1*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.3*	*0.6*	*0.1*	*0.3*	*0.6*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*8*	*20*	*40*	*8*	*20*	*40*
Time (days)	*10*	*14*	*20*	*10*	*14*	*20*
	MT 2	*Choice 2*		**MT 2**	*Choice 2*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.3*	*0.6*	*0.1*	*0.3*	*0.6*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*4*	*8*	*12*	*4*	*8*	*12*
Time (days)	*10*	*14*	*20*	*10*	*14*	*20*
	MT 3	*Choice 3*		**MT 3**	*Choice 3*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.2*	*0.4*	*0.4*	*0.05*	*0.8*	*0.15*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*8*	*16*	*24*	*8*	*16*	*24*
Time (days)	*45*	*90*	*120*	*45*	*90*	*120*
	MT 4	*Choice 4*		**MT 4**	*Choice 4*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.7*	*0.2*	*0.05*	*0.85*	*0.1*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*8*	*16*	*24*	*8*	*16*	*24*
Time (days)	*45*	*90*	*120*	*45*	*90*	*120*
	MT 5	*Choice 5*		**MT 5**	*Choice 5*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.7*	*0.2*	*0.1*	*0.3*	*0.6*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*8*	*16*	*24*	*4*	*8*	*12*
Time (days)	*45*	*90*	*120*	*10*	*30*	*45*

	Root Cause 3			***Root Cause 4***		
	MT 1	*Choice 1*		**MT 1**	*Choice 1*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.3*	*0.6*	*0.1*	*0.3*	*0.6*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*4*	*10*	*20*	*4*	*10*	*20*
Time (days)	*5*	*7*	*10*	*5*	*7*	*10*
	MT 2	*Choice 2*		**MT 2**	*Choice 2*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.3*	*0.6*	*0.1*	*0.3*	*0.6*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*4*	*8*	*12*	*2*	*4*	*6*
Time (days)	*10*	*14*	*20*	*5*	*7*	*10*
	MT 3	*Choice 3*		**MT 3**	*Choice 3*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.3*	*0.4*	*0.3*	*0.2*	*0.5*	*0.3*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*8*	*16*	*24*	*8*	*16*	*24*
Time (days)	*20*	*45*	*90*	*20*	*60*	*90*
	MT 4	*Choice 4*		**MT 4**	*Choice 4*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.3*	*0.4*	*0.3*	*0.2*	*0.5*	*0.3*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*8*	*16*	*24*	*8*	*16*	*24*
Time (days)	*45*	*90*	*120*	*45*	*90*	*120*
	MT 5	*Choice 5*		**MT 5**	*Choice 5*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.05*	*0.8*	*0.15*	*0.05*	*0.8*	*0.15*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*8*	*16*	*24*	*8*	*16*	*24*
Time (days)	*45*	*90*	*120*	*45*	*90*	*120*

SC1 RISK

	Root Cause 1			***Root Cause 2***			***Root Cause 3***		
	MT 1	*Choice 1*		**MT 1**	*Choice 1*		**MT 1**	*Choice 1*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	0.2	0.2	0.6	0.2	0.5	0.3	0.1	0.5	0.4
Cost ($)	10000	14000	20000	5000	10000	14000	5000	10000	14000
People	8	12	20	4	8	12	4	8	12
Time (days)	60	120	180	20	40	60	15	25	35
	MT 2	*Choice 7*		**MT 2**	*Choice 3*		**MT 2**	*Choice 3*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	0.05	0.8	0.15	0.25	0.65	0.1	0.1	0.8	0.1
Cost ($)	5000	7500	10000	250	500	1000	250	500	1000
People	4	8	16	8	12	20	8	12	20
Time (days)	30	60	120	10	20	30	10	20	30
				MT 3	*Choice 4*		**MT 3**	*Choice 4*	
				Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability				0.2	0.7	0.1	0.1	0.7	0.2
Cost ($)				250	500	1000	250	500	1000
People				8	12	20	8	12	20
Time (days)				10	20	30	10	20	30
				MT 4	*Choice 5*		**MT 4**	*Choice 5*	
				Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability				0.1	0.8	0.1	0.25	0.65	0.1
Cost ($)				250	500	1000	250	500	1000
People				8	12	20	8	12	20
Time (days)				10	20	30	10	20	30
				MT 5	*Choice 6*		**MT 5**	*Choice 6*	
				Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability				0.1	0.8	0.1	0.1	0.8	0.1
Cost ($)				100	200	300	100	200	300
People				4	6	8	4	6	8
Time (days)				15	20	25	15	20	25
				MT 6	*Choice 8*		**MT 6**	*Choice 8*	
				Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability				0.1	0.6	0.3	0.1	0.7	0.2
Cost ($)				0	0	0	0	0	0
People				4	8	12	4	8	12
Time (days)				15	20	25	15	20	25

	Root Cause 4			*Root Cause 5*		
	MT 1	*Choice 1*		**MT 1**	*Choice 1*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.6*	*0.3*	*0.1*	*0.6*	*0.3*
Cost ($)	*10000*	*14000*	*20000*	*5000*	*10000*	*14000*
People	*8*	*12*	*20*	*8*	*12*	*20*
Time (days)	*60*	*120*	*180*	*20*	*30*	*60*
	MT 2	*Choice 3*		**MT 2**	*Choice 3*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.65*	*0.25*	*0.15*	*0.75*	*0.1*
Cost ($)	*250*	*500*	*1000*	*250*	*500*	*1000*
People	*8*	*12*	*20*	*8*	*12*	*20*
Time (days)	*10*	*20*	*30*	*10*	*20*	*30*
	MT 3	*Choice 4*		**MT 3**	*Choice 4*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.7*	*0.2*	*0.1*	*0.7*	*0.2*
Cost ($)	*250*	*500*	*1000*	*250*	*500*	*1000*
People	*8*	*12*	*20*	*8*	*12*	*20*
Time (days)	*10*	*20*	*30*	*10*	*20*	*30*
	MT 4	*Choice 5*		**MT 4**	*Choice 5*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.8*	*0.1*	*0.1*	*0.8*	*0.1*
Cost ($)	*250*	*500*	*1000*	*250*	*500*	*1000*
People	*8*	*12*	*20*	*8*	*12*	*20*
Time (days)	*10*	*20*	*30*	*10*	*20*	*30*
	MT 5	*Choice 6*		**MT 5**	*Choice 6*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.8*	*0.1*	*0.1*	*0.8*	*0.1*
Cost ($)	*100*	*200*	*300*	*100*	*200*	*300*
People	*4*	*6*	*8*	*4*	*6*	*8*
Time (days)	*15*	*20*	*25*	*15*	*20*	*25*
	MT 6	*Choice 8*		**MT 6**	*Choice 8*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.8*	*0.1*	*0.1*	*0.65*	*0.25*
Cost ($)	*100*	*200*	*300*	*100*	*200*	*300*
People	*4*	*6*	*8*	*4*	*6*	*8*
Time (days)	*15*	*20*	*25*	*15*	*20*	*25*

SC2 RISK

	Root Cause 1			***Root Cause 2***			***Root Cause 3***		
	MT 1	*Choice 1*		**MT 1**	*Choice 1*		**MT 1**	*Choice 1*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.6*	*0.3*	*0.1*	*0.6*	*0.3*	*0.1*	*0.6*	*0.3*
Cost ($)	*500*	*1000*	*1500*	*1500*	*12000*	*24000*	*1500*	*20000*	*60000*
People	*8*	*12*	*20*	*4*	*8*	*12*	*4*	*8*	*12*
Time (days)	*60*	*120*	*180*	*10*	*45*	*80*	*10*	*45*	*80*
	MT 2	*Choice 2*		**MT 2**	*Choice 2*		**MT 2**	*Choice 2*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.7*	*0.2*	*0.1*	*0.7*	*0.2*	*0.1*	*0.7*	*0.2*
Cost ($)	*250*	*500*	*1000*	*1500*	*12000*	*24000*	*1500*	*20000*	*60000*
People	*8*	*12*	*20*	*8*	*16*	*20*	*8*	*16*	*20*
Time (days)	*20*	*40*	*60*	*20*	*60*	*90*	*20*	*60*	*90*
	MT 3	*Choice 3*		**MT 3**	*Choice 3*		**MT 3**	*Choice 3*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.8*	*0.1*	*0.1*	*0.8*	*0.1*	*0.1*	*0.8*	*0.1*
Cost ($)	*500*	*1000*	*1500*	*1500*	*12000*	*24000*	*1500*	*20000*	*60000*
People	*12*	*24*	*30*	*12*	*24*	*30*	*12*	*24*	*30*
Time (days)	*30*	*60*	*90*	*30*	*60*	*90*	*15*	*60*	*180*
	MT 4	*Choice 6*		**MT 4**	*Choice 7*		**MT 4**	*Choice 7*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.8*	*0.1*	*0.1*	*0.8*	*0.1*	*0.1*	*0.8*	*0.1*
Cost ($)	*500*	*1000*	*1500*	*1500*	*12000*	*24000*	*1500*	*20000*	*60000*
People	*12*	*24*	*30*	*8*	*16*	*20*	*8*	*16*	*20*
Time (days)	*30*	*60*	*90*	*20*	*60*	*90*	*15*	*60*	*180*
	MT 5	*Choice 7*		**MT 5**	*Choice 8*		**MT 5**	*Choice 8*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.8*	*0.1*	*0.1*	*0.7*	*0.2*	*0.1*	*0.7*	*0.2*
Cost ($)	*500*	*1000*	*1500*	*1500*	*12000*	*24000*	*1500*	*20000*	*60000*
People	*12*	*24*	*30*	*4*	*8*	*12*	*4*	*8*	*12*
Time (days)	*30*	*60*	*90*	*10*	*60*	*90*	*5*	*60*	*180*
	MT 6	*Choice 8*		**MT 6**	*Choice 10*		**MT 6**	*Choice 10*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.7*	*0.2*	*0.2*	*0.4*	*0.4*	*0.2*	*0.4*	*0.4*
Cost ($)	*500*	*1000*	*1500*	*2000*	*12000*	*24000*	*3000*	*20000*	*60000*
People	*12*	*24*	*30*	*4*	*6*	*10*	*4*	*6*	*10*
Time (days)	*30*	*60*	*90*	*60*	*90*	*180*	*60*	*90*	*180*

	Root Cause 4			***Root Cause 5***		
	MT 1	*Choice 1*		**MT 1**	*Choice 1*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.3*	*0.6*	*0.1*	*0.3*	*0.6*	*0.1*
Cost ($)	*1000*	*3500*	*7000*	*1000*	*2000*	*9500*
People	*4*	*8*	*12*	*4*	*8*	*12*
Time (days)	*10*	*30*	*60*	*10*	*30*	*120*
	MT 2	*Choice 2*		**MT 2**	*Choice 2*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.2*	*0.7*	*0.1*	*0.2*	*0.7*	*0.1*
Cost ($)	*1000*	*3500*	*7000*	*1000*	*2000*	*9500*
People	*8*	*16*	*20*	*8*	*16*	*20*
Time (days)	*10*	*30*	*60*	*5*	*15*	*90*
	MT 3	*Choice 3*		**MT 3**	*Choice 3*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.8*	*0.1*	*0.1*	*0.8*	*0.1*
Cost ($)	*1000*	*3500*	*7000*	*1000*	*2000*	*9500*
People	*6*	*12*	*15*	*6*	*12*	*15*
Time (days)	*5*	*15*	*42*	*5*	*15*	*90*
	MT 4	*Choice 7*		**MT 4**	*Choice 7*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.8*	*0.1*	*0.1*	*0.8*	*0.1*
Cost ($)	*1000*	*3500*	*7000*	*1000*	*2000*	*9500*
People	*4*	*8*	*10*	*8*	*16*	*20*
Time (days)	*30*	*60*	*90*	*20*	*30*	*120*
	MT 5	*Choice 9*		**MT 5**	*Choice 9*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.8*	*0.1*	*0.1*	*0.8*	*0.1*
Cost ($)	*1000*	*3500*	*7000*	*1000*	*2000*	*9500*
People	*4*	*8*	*12*	*4*	*8*	*12*
Time (days)	*10*	*30*	*60*	*10*	*30*	*120*
	MT 6	*Choice 10*		**MT 6**	*Choice 10*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.2*	*0.4*	*0.4*	*0.2*	*0.4*	*0.4*
Cost ($)	*3500*	*7000*	*14000*	*2000*	*7500*	*9500*
People	*4*	*6*	*10*	*4*	*6*	*10*
Time (days)	*60*	*90*	*180*	*15*	*90*	*90*

	Root Cause 6			***Root Cause 7***		
	MT 1	*Choice 7*		**MT 1**	*Choice 12*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.25*	*0.65*	*0.1*	*0.1*	*0.8*	*0.1*
Cost ($)	*250*	*500*	*1000*	*250*	*500*	*1000*
People	*8*	*16*	*20*	*16*	*32*	*48*
Time (days)	*10*	*30*	*60*	*20*	*60*	*90*
	MT 2	*Choice 12*		**MT 2**	*Choice 14*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.8*	*0.1*	*0.15*	*0.75*	*0.1*
Cost ($)	*250*	*500*	*1000*	*250*	*500*	*1000*
People	*16*	*32*	*48*	*8*	*16*	*20*
Time (days)	*20*	*60*	*90*	*30*	*60*	*90*
	MT 3	*Choice 13*		**MT 3**	*Choice 16*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.15*	*0.75*	*0.1*	*0.2*	*0.7*	*0.1*
Cost ($)	*250*	*500*	*1000*	*250*	*500*	*1000*
People	*8*	*16*	*20*	*8*	*12*	*16*
Time (days)	*30*	*60*	*90*	*60*	*90*	*120*
	MT 4	*Choice 15*				
	Fully	**Partially**	**Doesn't**			
Probability	*0.2*	*0.7*	*0.1*			
Cost ($)	*250*	*500*	*1000*			
People	*8*	*12*	*16*			
Time (days)	*60*	*90*	*120*			
	MT 5	*Choice 3*				
	Fully	**Partially**	**Doesn't**			
Probability	*0.25*	*0.65*	*0.1*			
Cost ($)	*250*	*500*	*1000*			
People	*4*	*8*	*16*			
Time (days)	*20*	*30*	*45*			

SC3 RISK

	Root Cause 1			***Root Cause 2***		
	MT 1	*Choice 1*		**MT 1**	*Choice 1*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.8*	*0.1*	*0.1*	*0.8*	*0.1*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*4*	*6*	*10*	*4*	*6*	*10*
Time (days)	*30*	*60*	*90*	*30*	*60*	*90*
	MT 2	*Alternate #1*		**MT 2**	*Choice 2*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.3*	*0.6*	*0.1*	*0.15*	*0.75*	*0.1*
Cost ($)	*1000*	*2000*	*3000*	*400*	*800*	*1200*
People	*12*	*20*	*30*	*4*	*8*	*12*
Time (days)	*120*	*180*	*240*	*20*	*40*	*60*
				MT 3	*Choice 3*	
				Fully	**Partially**	**Doesn't**
				0.25	*0.65*	*0.1*
				1000	*3000*	*6000*
				4	*8*	*12*
				20	*40*	*60*
				MT 4	*Choice 6*	
				Fully	**Partially**	**Doesn't**
				0.1	*0.8*	*0.1*
				0	*0*	*0*
				20	*40*	*60*
				4	*10*	*20*

	Root Cause 3			***Root Cause 4***		
	MT 1	*Choice 4*		**MT 1**	*Choice 1*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.7*	*0.2*	*0.1*	*0.7*	*0.2*
Cost ($)	*100*	*200*	*300*	*0*	*0*	*0*
People	*4*	*8*	*12*	*8*	*12*	*20*
Time (days)	*20*	*40*	*60*	*60*	*120*	*180*
	MT 2	*Choice 5*		**MT 2**	*Choice 6*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.8*	*0.1*	*0.1*	*0.8*	*0.1*
Cost ($)	*100*	*200*	*300*	*0*	*0*	*0*
People	*12*	*16*	*20*	*15*	*25*	*35*
Time (days)	*30*	*60*	*90*	*5*	*10*	*15*
	MT 3	*Choice 6*				
	Fully	**Partially**	**Doesn't**			
Probability	*0.2*	*0.2*	*0.6*			
Cost ($)	*0*	*0*	*0*			
People	*15*	*25*	*35*			
Time (days)	*5*	*10*	*15*			

PER RISK

	Root Cause 1			*Root Cause 2*			*Root Cause 3*		
	MT 1	*Choice 3*		**MT 1**	*Choice 1*		**MT 1**	*Choice 1*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.8*	*0.1*	*0.2*	*0.4*	*0.4*	*0.15*	*0.8*	*0.05*
Cost ($)	*200*	*400*	*600*	*40000*	*80000*	*120000*	*40000*	*80000*	*120000*
People	*4*	*8*	*12*	*2*	*10*	*20*	*2*	*10*	*20*
Time (days)	*8*	*20*	*30*	*10*	*30*	*60*	*10*	*30*	*60*
	MT 2	*Choice 4*		**MT 2**	*Choice 6*		**MT 2**	*Choice 2*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.2*	*0.5*	*0.3*	*0.1*	*0.8*	*0.1*	*0.15*	*0.8*	*0.05*
Cost ($)	*100*	*200*	*300*	*1000*	*2000*	*10000*	*0*	*0*	*0*
People	*6*	*18*	*24*	*4*	*8*	*12*	*6*	*12*	*18*
Time (days)	*20*	*60*	*90*	*2*	*10*	*20*	*2*	*10*	*20*
	MT 3	*Choice 5*		**MT 3**	*Choice 7*		**MT 3**	*Choice 4*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.3*	*0.4*	*0.3*	*0.2*	*0.6*	*0.2*	*0.2*	*0.5*	*0.3*
Cost ($)	*0*	*0*	*0*	*1000*	*2000*	*5000*	*100*	*200*	*300*
People	*4*	*8*	*12*	*4*	*8*	*12*	*6*	*18*	*24*
Time (days)	*4*	*10*	*20*	*2*	*10*	*20*	*20*	*60*	*90*
	MT 4	*Choice 10*		**MT 4**	*Choice 11*		**MT 4**	*Choice 10*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.3*	*0.4*	*0.3*	*0.15*	*0.8*	*0.05*	*0.1*	*0.85*	*0.05*
Cost ($)	*200*	*400*	*600*	*100*	*200*	*300*	*200*	*400*	*600*
People	*6*	*18*	*24*	*4*	*8*	*12*	*6*	*18*	*24*
Time (days)	*20*	*60*	*90*	*2*	*10*	*20*	*20*	*60*	*90*

	Root Cause 4			Root Cause 5		
	MT 1	*Choice 1*		**MT 1**	*Choice 1*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.15*	*0.8*	*0.05*	*0.15*	*0.7*	*0.15*
Cost ($)	*40000*	*80000*	*120000*	*40000*	*80000*	*120000*
People	*2*	*10*	*20*	*2*	*10*	*20*
Time (days)	*10*	*30*	*60*	*10*	*30*	*60*
	MT 2	*Choice 3*		**MT 2**	*Choice 3*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.6*	*0.3*	*0.1*	*0.6*	*0.3*
Cost ($)	*200*	*400*	*600*	*200*	*400*	*600*
People	*4*	*8*	*12*	*4*	*8*	*12*
Time (days)	*8*	*20*	*30*	*8*	*20*	*30*
	MT 3	*Choice 4*		**MT 3**	*Choice 4*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.7*	*0.2*	*0.05*	*0.8*	*0.15*
Cost ($)	*100*	*200*	*300*	*100*	*200*	*300*
People	*6*	*18*	*24*	*6*	*18*	*24*
Time (days)	*20*	*60*	*90*	*20*	*60*	*90*
	MT 4	*Choice 7*		**MT 4**	*Choice 7*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.2*	*0.6*	*0.2*	*0.2*	*0.5*	*0.3*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*4*	*8*	*12*	*4*	*8*	*12*
Time (days)	*2*	*10*	*20*	*2*	*10*	*20*
	MT 5	*Choice 8*		**MT 5**	*Choice 8*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.7*	*0.2*	*0.2*	*0.5*	*0.3*
Cost ($)	*100*	*200*	*400*	*100*	*200*	*400*
People	*4*	*8*	*12*	*4*	*8*	*12*
Time (days)	*2*	*8*	*10*	*2*	*8*	*10*
	MT 6	*Alternate #1*		**MT 6**	*Choice 9*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.2*	*0.6*	*0.2*	*0.1*	*0.8*	*0.1*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*8*	*12*	*20*	*6*	*18*	*24*
Time (days)	*20*	*60*	*90*	*20*	*60*	*90*

COST RISK

	Root Cause 1			***Root Cause 2***		
	MT 1	*Choice 1*		**MT 1**	*Choice 1*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.05*	*0.9*	*0.05*	*0.2*	*0.2*	*0.6*
Cost ($)	*100*	*200*	*300*	*100*	*200*	*300*
People	*4*	*8*	*12*	*4*	*8*	*12*
Time (days)	*2*	*10*	*20*	*4*	*10*	*20*
	MT 2	*Choice 2*		**MT 2**	*Choice 2*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.7*	*0.2*	*0.05*	*0.8*	*0.15*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*4*	*6*	*2*	*4*	*6*
Time (days)	*1*	*2*	*4*	*1*	*2*	*4*
	MT 3	*Choice 3*		**MT 3**	*Choice 3*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.05*	*0.8*	*0.15*	*0.1*	*0.9*	*0*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*4*	*6*	*2*	*4*	*6*
Time (days)	*1*	*2*	*4*	*1*	*2*	*4*
	MT 4	*Choice 4*		**MT 4**	*Choice 4*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.6*	*0.3*	*0.2*	*0.4*	*0.4*
Cost ($)	*200*	*400*	*1000*	*200*	*400*	*1000*
People	*8*	*16*	*24*	*8*	*16*	*24*
Time (days)	*10*	*30*	*60*	*10*	*30*	*60*
	MT 5	*Choice 5*		**MT 5**	*Choice 5*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.2*	*0.5*	*0.3*	*0.1*	*0.7*	*0.2*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*8*	*16*	*24*	*8*	*16*	*24*
Time (days)	*10*	*30*	*60*	*10*	*30*	*60*
	MT 6	*Choice 6*		**MT 6**	*Choice 6*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.2*	*0.6*	*0.2*	*0.1*	*0.8*	*0.1*
Cost ($)	*2000*	*10000*	*20000*	*2000*	*10000*	*20000*
People	*8*	*16*	*24*	*8*	*16*	*24*
Time (days)	*30*	*60*	*90*	*30*	*60*	*90*

	Root Cause 3			***Root Cause 4***		
	MT 1	*Choice 1*		**MT 1**	*Choice 1*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.2*	*0.2*	*0.6*	*0.2*	*0.2*	*0.6*
Cost ($)	*100*	*200*	*300*	*100*	*200*	*300*
People	*4*	*8*	*12*	*4*	*8*	*12*
Time (days)	*2*	*10*	*20*	*2*	*10*	*20*
	MT 2	*Choice 2*		**MT 2**	*Choice 2*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.2*	*0.2*	*0.6*	*0.2*	*0.2*	*0.6*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*4*	*6*	*2*	*4*	*6*
Time (days)	*1*	*2*	*4*	*1*	*2*	*4*
	MT 3	*Choice 3*		**MT 3**	*Choice 3*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.1*	*0.8*	*0.1*	*0.1*	*0.8*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*4*	*6*	*2*	*4*	*6*
Time (days)	*1*	*2*	*4*	*1*	*2*	*4*
	MT 4	*Choice 4*		**MT 4**	*Choice 4*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.1*	*0.8*	*0.3*	*0.3*	*0.4*
Cost ($)	*200*	*400*	*1000*	*200*	*400*	*1000*
People	*8*	*16*	*24*	*8*	*16*	*24*
Time (days)	*10*	*30*	*60*	*10*	*30*	*60*
	MT 5	*Choice 5*		**MT 5**	*Choice 5*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.1*	*0.8*	*0.3*	*0.3*	*0.4*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*8*	*16*	*24*	*8*	*16*	*24*
Time (days)	*10*	*30*	*60*	*10*	*30*	*60*
	MT 6	*Choice 6*		**MT 6**	*Choice 6*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.7*	*0.2*	*0.1*	*0.7*	*0.2*
Cost ($)	*2000*	*10000*	*20000*	*2000*	*10000*	*20000*
People	*8*	*16*	*24*	*8*	*16*	*24*
Time (days)	*30*	*60*	*90*	*30*	*60*	*90*

PREFERENCE SYSTEM

	Gamma	**K**	0
Time	0.01	**K1**	0.7
Cost	0.0001	**K2**	0.7
People	0.05	**K3**	0.7

Appendix C: Testing Life Cycle Phase Data

Recall that the highlighted values represent values changed from the ARMADILLO case study from Appendix A.

SCHEDULE RISK

	Root Cause 1			***Root Cause 2***			***Root Cause 3***		
	MT 1	*Choice 1*		**MT 1**	*Choice 1*		**MT 1**	*Choice 1*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.4*	*0.5*	*0.5*	*0.3*	*0.2*	*0.5*	*0.3*	*0.2*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
People	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*
Time (days)	*2*	*3*	*5*	*2*	*3*	*5*	*2*	*3*	*5*
	MT 2	*Choice 2*		**MT 2**	*Choice 2*		**MT 2**	*Choice 2*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.4*	*0.5*	*0.2*	*0.3*	*0.5*	*0.4*	*0.4*	*0.2*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
People	*1*	*2*	*5*	*1*	*2*	*5*	*1*	*2*	*5*
Time (days)	*1*	*3*	*5*	*2*	*3*	*5*	*1*	*7*	*15*
	MT 3	*Choice 3*		**MT 3**	*Choice 3*		**MT 3**	*Choice 3*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.3*	*0.6*	*0.1*	*0.3*	*0.6*	*0.25*	*0.5*	*0.25*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*5*	*10*	*2*	*5*	*10*	*2*	*5*	*10*
Time (days)	*2*	*3*	*5*	*2*	*3*	*5*	*2*	*15*	*45*
	MT 4	*Choice 4*		**MT 4**	*Choice 4*		**MT 4**	*Choice 4*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.6*	*0.3*	*0.1*	*0.3*	*0.6*	*0.1*	*0.3*	*0.6*	*0.1*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
People	*1*	*2*	*3*	*1*	*2*	*2*	*1*	*2*	*4*
Time (days)	*2*	*3*	*5*	*2*	*3*	*5*	*2*	*7*	*15*
	MT 5	*Choice 5*		**MT 5**	*Choice 5*		**MT 5**	*Choice 5*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.4*	*0.5*	*0.2*	*0.5*	*0.3*	*0.1*	*0.2*	*0.7*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*5*	*7*	*2*	*5*	*7*	*2*	*5*	*7*
Time (days)	*2*	*5*	*7*	*2*	*5*	*7*	*2*	*5*	*7*
	MT 6	*Choice 6*		**MT 6**	*Choice 6*		**MT 6**	*Choice 6*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.8*	*0.15*	*0.05*	*0.8*	*0.15*	*0.05*	*0.8*	*0.15*	*0.05*
Cost ($)	*0*	*250*	*500*	*0*	*250*	*500*	*0*	*500*	*1000*
People	*0*	*2*	*5*	*0*	*2*	*5*	*1*	*2*	*5*
Time (days)	*0*	*2*	*5*	*0*	*2*	*5*	*1*	*2*	*5*

	Root Cause 4			***Root Cause 5***		
	MT 1	*Choice 1*		**MT 1**	*Choice 1*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.5*	*0.3*	*0.2*	*0.5*	*0.3*	*0.2*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*1*	*2*	*3*	*1*	*2*	*3*
Time (days)	*2*	*3*	*5*	*2*	*3*	*7*
	MT 1	*Choice 2*		**MT 2**	*Choice 2*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.2*	*0.4*	*0.4*	*0.4*	*0.4*	*0.2*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*1*	*2*	*5*	*1*	*2*	*5*
Time (days)	*1*	*7*	*15*	*1*	*3*	*7*
	MT 3	*Choice 3*		**MT 3**	*Choice 3*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.7*	*0.25*	*0.05*	*0.3*	*0.6*	*0.1*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*5*	*10*	*2*	*5*	*10*
Time (days)	*2*	*15*	*45*	*2*	*7*	*15*
	MT 4	*Choice 4*		**MT 4**	*Choice 4*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.5*	*0.3*	*0.2*	*0.6*	*0.3*	*0.1*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*1*	*2*	*4*	*1*	*2*	*4*
Time (days)	*2*	*7*	*15*	*2*	*7*	*15*
	MT 5	*Choice 5*		**MT 5**	*Choice 5*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.2*	*0.7*	*0.8*	*0.15*	*0.05*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*5*	*7*	*2*	*5*	*7*
Time (days)	*2*	*5*	*7*	*2*	*5*	*7*
	MT 6	*Choice 6*		**MT 6**	*Choice 6*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.8*	*0.15*	*0.05*	*0.7*	*0.2*	*0.1*
Cost ($)	*0*	*500*	*1000*	*0*	*0*	*0*
People	*1*	*2*	*5*	*1*	*2*	*5*
Time (days)	*1*	*2*	*5*	*1*	*2*	*5*

PAYLOAD RISK

	Root Cause 1			***Root Cause 2***		
	MT 1	*Choice 1*		**MT 1**	*Choice 1*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.3*	*0.6*	*0.1*	*0.3*	*0.6*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*5*	*10*	*2*	*5*	*10*
Time (days)	*2*	*3*	*5*	*2*	*3*	*5*
	MT 2	*Choice 2*		**MT 2**	*Choice 2*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.3*	*0.6*	*0.1*	*0.3*	*0.6*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*1*	*2*	*3*	*1*	*2*	*3*
Time (days)	*2*	*3*	*5*	*2*	*3*	*5*
	MT 3	*Choice 3*		**MT 3**	*Choice 3*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.4*	*0.4*	*0.2*	*0.8*	*0.15*	*0.05*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*4*	*6*	*2*	*4*	*6*
Time (days)	*5*	*15*	*22*	*5*	*15*	*22*
	MT 4	*Choice 4*		**MT 4**	*Choice 4*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.7*	*0.2*	*0.1*	*0.85*	*0.1*	*0.05*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*4*	*6*	*2*	*4*	*6*
Time (days)	*5*	*15*	*22*	*5*	*15*	*22*
	MT 5	*Choice 5*		**MT 5**	*Choice 5*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.7*	*0.2*	*0.1*	*0.1*	*0.3*	*0.6*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*4*	*6*	*2*	*4*	*6*
Time (days)	*5*	*15*	*22*	*5*	*15*	*22*

	Root Cause 3			***Root Cause 4***		
	MT 1	*Choice 1*		**MT 1**	*Choice 1*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.3*	*0.6*	*0.1*	*0.3*	*0.6*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*5*	*10*	*2*	*5*	*10*
Time (days)	*2*	*3*	*5*	*2*	*3*	*5*
	MT 2	*Choice 1*		**MT 2**	*Choice 2*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.3*	*0.6*	*0.1*	*0.3*	*0.6*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*1*	*2*	*3*	*1*	*2*	*3*
Time (days)	*2*	*3*	*5*	*2*	*3*	*5*
	MT 3	*Choice 3*		**MT 3**	*Choice 2*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.3*	*0.4*	*0.3*	*0.3*	*0.4*	*0.3*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*4*	*6*	*2*	*4*	*6*
Time (days)	*5*	*15*	*22*	*5*	*15*	*22*
	MT 4	*Choice 4*		**MT 4**	*Choice 4*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.3*	*0.4*	*0.3*	*0.3*	*0.4*	*0.3*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*4*	*6*	*2*	*4*	*6*
Time (days)	*5*	*15*	*22*	*5*	*15*	*22*
	MT 5	*Choice 5*		**MT 5**	*Choice 5*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.85*	*0.1*	*0.05*	*0.85*	*0.1*	*0.05*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*4*	*6*	*2*	*4*	*6*
Time (days)	*5*	*15*	*22*	*5*	*15*	*22*

SC1 RISK

	Root Cause 1			Root Cause 2			Root Cause 3		
	MT 1	*Choice 1*		**MT 1**	*Choice 1*		**MT 1**	*Choice 1*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.2*	*0.2*	*0.6*	*0.4*	*0.5*	*0.1*	*0.4*	*0.5*	*0.1*
Cost ($)	*2500*	*3450*	*5000*	*1250*	*2500*	*3450*	*1250*	*2500*	*3450*
People	*2*	*3*	*5*	*1*	*2*	*3*	*1*	*2*	*3*
Time (days)	*15*	*30*	*45*	*5*	*10*	*15*	*5*	*10*	*15*
	MT 2	*Choice 7*		**MT 2**	*Choice 3*		**MT 2**	*Choice 3*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.85*	*0.1*	*0.05*	*0.65*	*0.25*	*0.1*	*0.8*	*0.1*	*0.1*
Cost ($)	*0*	*2500*	*3450*	*0*	*0*	*0*	*0*	*0*	*0*
People	*1*	*2*	*4*	*2*	*3*	*5*	*2*	*3*	*5*
Time (days)	*7*	*15*	*30*	*2*	*5*	*7*	*2*	*5*	*7*
				MT 3	*Choice 4*		**MT 3**	*Choice 4*	
				Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability				*0.7*	*0.2*	*0.1*	*0.7*	*0.2*	*0.1*
Cost ($)				*0*	*0*	*0*	*0*	*0*	*0*
People				*2*	*3*	*5*	*2*	*3*	*5*
Time (days)				*2*	*5*	*7*	*2*	*5*	*7*
				MT 4	*Choice 5*		**MT 4**	*Choice 5*	
				Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability				*0.8*	*0.1*	*0.1*	*0.65*	*0.25*	*0.1*
Cost ($)				*0*	*0*	*0*	*0*	*0*	*0*
People				*2*	*3*	*5*	*2*	*3*	*5*
Time (days)				*2*	*5*	*7*	*2*	*5*	*7*
				MT 5	*Choice 6*		**MT 5**	*Choice 6*	
				Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability				*0.8*	*0.1*	*0.1*	*0.8*	*0.1*	*0.1*
Cost ($)				*0*	*0*	*0*	*0*	*0*	*0*
People				*1*	*2*	*3*	*1*	*2*	*3*
Time (days)				*5*	*7*	*10*	*5*	*7*	*10*
				MT 6	*Choice 8*		**MT 6**	*Choice 8*	
				Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability				*0.6*	*0.3*	*0.1*	*0.7*	*0.2*	*0.1*
Cost ($)				*0*	*0*	*0*	*0*	*0*	*0*
People				*1*	*2*	*3*	*1*	*2*	*3*
Time (days)				*5*	*7*	*10*	*5*	*7*	*10*

	Root Cause 4			Root Cause 5		
	MT 1	*Choice 1*		**MT 1**	*Choice 1*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.6*	*0.3*	*0.1*	*0.6*	*0.3*	*0.1*
Cost ($)	*2500*	*3450*	*5000*	*1250*	*2500*	*3450*
People	*2*	*3*	*5*	*2*	*3*	*5*
Time (days)	*15*	*22*	*30*	*5*	*7*	*15*
	MT 2	*Choice 3*		**MT 2**	*Choice 3*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.65*	*0.25*	*0.1*	*0.75*	*0.15*	*0.1*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*3*	*5*	*2*	*3*	*5*
Time (days)	*2*	*5*	*7*	*2*	*5*	*7*
	MT 3	*Choice 4*		**MT 3**	*Choice 4*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.7*	*0.2*	*0.1*	*0.7*	*0.2*	*0.1*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*3*	*5*	*2*	*3*	*5*
Time (days)	*2*	*5*	*7*	*2*	*5*	*7*
	MT 4	*Choice 5*		**MT 4**	*Choice 5*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.8*	*0.1*	*0.1*	*0.8*	*0.1*	*0.1*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*3*	*5*	*2*	*3*	*5*
Time (days)	*2*	*5*	*7*	*2*	*5*	*7*
	MT 5	*Choice 6*		**MT 5**	*Choice 6*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.8*	*0.1*	*0.1*	*0.8*	*0.1*	*0.1*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*1*	*2*	*3*	*1*	*2*	*3*
Time (days)	*5*	*7*	*10*	*5*	*7*	*10*
	MT 6	*Choice 8*		**MT 6**	*Choice 8*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.8*	*0.1*	*0.1*	*0.65*	*0.25*	*0.1*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*1*	*2*	*3*	*1*	*2*	*3*
Time (days)	*5*	*7*	*10*	*5*	*7*	*10*

SC2 RISK

	Root Cause 1			***Root Cause 2***			***Root Cause 3***		
	MT 1	*Choice 1*		**MT 1**	*Choice 1*		**MT 1**	*Choice 1*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.6*	*0.3*	*0.1*	*0.6*	*0.3*	*0.1*	*0.6*	*0.3*	*0.1*
Cost ($)	*0*	*250*	*500*	*0*	*6000*	*12000*	*0*	*10000*	*30000*
People	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*
Time (days)	*2*	*5*	*7*	*2*	*15*	*30*	*3*	*30*	*90*
	MT 2	*Choice 2*		**MT 2**	*Choice 2*		**MT 2**	*Choice 2*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.7*	*0.2*	*0.1*	*0.7*	*0.2*	*0.1*	*0.7*	*0.2*	*0.1*
Cost ($)	*0*	*250*	*500*	*0*	*6000*	*12000*	*0*	*10000*	*30000*
People	*2*	*4*	*5*	*2*	*4*	*5*	*2*	*4*	*5*
Time (days)	*5*	*10*	*15*	*5*	*15*	*30*	*5*	*30*	*90*
	MT 3	*Choice 3*		**MT 3**	*Choice 3*		**MT 3**	*Choice 3*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.8*	*0.1*	*0.1*	*0.8*	*0.1*	*0.1*	*0.8*	*0.1*	*0.1*
Cost ($)	*0*	*250*	*500*	*0*	*6000*	*12000*	*0*	*10000*	*30000*
People	*3*	*6*	*7*	*3*	*6*	*7*	*3*	*6*	*7*
Time (days)	*7*	*15*	*22*	*7*	*15*	*30*	*7*	*30*	*90*
	MT 4	*Choice 6*		**MT 4**	*Choice 7*		**MT 4**	*Choice 7*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.8*	*0.1*	*0.1*	*0.8*	*0.1*	*0.1*	*0.8*	*0.1*	*0.1*
Cost ($)	*0*	*250*	*500*	*0*	*6000*	*12000*	*0*	*10000*	*30000*
People	*2*	*4*	*5*	*2*	*4*	*5*	*2*	*4*	*5*
Time (days)	*5*	*10*	*15*	*7*	*15*	*30*	*7*	*30*	*90*
	MT 5	*Choice 7*		**MT 5**	*Choice 8*		**MT 5**	*Choice 8*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.8*	*0.1*	*0.1*	*0.7*	*0.2*	*0.1*	*0.7*	*0.2*	*0.1*
Cost ($)	*0*	*250*	*500*	*0*	*6000*	*12000*	*0*	*10000*	*30000*
People	*2*	*4*	*5*	*1*	*2*	*3*	*1*	*2*	*3*
Time (days)	*5*	*10*	*15*	*2*	*15*	*30*	*2*	*30*	*90*
	MT 6	*Choice 8*		**MT 6**	*Choice 10*		**MT 6**	*Choice 10*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.7*	*0.2*	*0.1*	*0.2*	*0.4*	*0.4*	*0.2*	*0.4*	*0.4*
Cost ($)	*0*	*250*	*500*	*1000*	*6000*	*12000*	*1500*	*10000*	*30000*
People	*1*	*2*	*3*	*2*	*3*	*5*	*2*	*3*	*5*
Time (days)	*2*	*5*	*7*	*30*	*45*	*90*	*30*	*45*	*90*

	Root Cause 4			***Root Cause 5***		
	MT 1	*Choice 1*		**MT 1**	*Choice 1*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.6*	*0.3*	*0.1*	*0.6*	*0.3*	*0.1*
Cost ($)	*0*	*1750*	*3500*	*0*	*1000*	*4750*
People	*1*	*2*	*3*	*1*	*2*	*3*
Time (days)	*2*	*7*	*21*	*2*	*7*	*45*
	MT 2	*Choice 2*		**MT 2**	*Choice 2*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.7*	*0.2*	*0.1*	*0.7*	*0.2*	*0.1*
Cost ($)	*0*	*1750*	*3500*	*0*	*1000*	*4750*
People	*2*	*4*	*5*	*2*	*4*	*5*
Time (days)	*2*	*7*	*21*	*2*	*7*	*45*
	MT 3	*Choice 3*		**MT 3**	*Choice 3*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.8*	*0.1*	*0.1*	*0.8*	*0.1*	*0.1*
Cost ($)	*0*	*1750*	*3500*	*0*	*1000*	*4750*
People	*3*	*6*	*7*	*3*	*6*	*7*
Time (days)	*2*	*7*	*21*	*2*	*7*	*45*
	MT 4	*Choice 7*		**MT 4**	*Choice 7*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.8*	*0.1*	*0.1*	*0.8*	*0.1*	*0.1*
Cost ($)	*0*	*1750*	*3500*	*0*	*1000*	*4750*
People	*2*	*4*	*5*	*2*	*4*	*5*
Time (days)	*5*	*7*	*21*	*5*	*7*	*45*
	MT 5	*Choice 9*		**MT 5**	*Choice 9*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.8*	*0.1*	*0.1*	*0.8*	*0.1*	*0.1*
Cost ($)	*0*	*1750*	*3500*	*0*	*1000*	*4750*
People	*1*	*2*	*3*	*1*	*2*	*3*
Time (days)	*2*	*7*	*21*	*2*	*7*	*45*
	MT 6	*Choice 10*		**MT 6**	*Choice 10*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.2*	*0.4*	*0.4*	*0.2*	*0.4*	*0.4*
Cost ($)	*1750*	*3500*	*7000*	*2000*	*7500*	*9500*
People	*2*	*3*	*5*	*2*	*3*	*5*
Time (days)	*30*	*45*	*90*	*7*	*45*	*45*

	Root Cause 6			Root Cause 7		
	MT 1	*Choice 7*		**MT 1**	*Choice 12*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.65*	*0.25*	*0.1*	*0.8*	*0.1*	*0.1*
Cost ($)	*0*	*250*	*500*	*0*	*250*	*500*
People	*2*	*4*	*5*	*4*	*8*	*12*
Time (days)	*2*	*7*	*15*	*5*	*15*	*30*
	MT 2	*Choice 12*		**MT 2**	*Choice 14*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.8*	*0.1*	*0.1*	*0.75*	*0.15*	*0.1*
Cost ($)	*0*	*250*	*500*	*0*	*250*	*500*
People	*4*	*8*	*12*	*2*	*4*	*5*
Time (days)	*5*	*15*	*30*	*5*	*15*	*30*
	MT 3	*Choice 13*		**MT 3**	*Choice 16*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.75*	*0.15*	*0.1*	*0.7*	*0.2*	*0.1*
Cost ($)	*0*	*250*	*500*	*0*	*250*	*500*
People	*2*	*4*	*5*	*2*	*3*	*4*
Time (days)	*5*	*15*	*30*	*15*	*30*	*45*
	MT 4	*Choice 15*				
	Fully	**Partially**	**Doesn't**			
Probability	*0.7*	*0.2*	*0.1*			
Cost ($)	*0*	*250*	*500*			
People	*2*	*3*	*4*			
Time (days)	*15*	*30*	*45*			
	MT 5	*Choice 3*				
	Fully	**Partially**	**Doesn't**			
Probability	*0.65*	*0.25*	*0.1*			
Cost ($)	*0*	*250*	*500*			
People	*1*	*2*	*4*			
Time (days)	*5*	*7*	*15*			

SC3 RISK

	Root Cause 1			Root Cause 2		
	MT 1	*Choice 1*		**MT 1**	*Choice 1*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.8*	*0.1*	*0.1*	*0.8*	*0.1*	*0.1*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*3*	*5*	*2*	*3*	*5*
Time (days)	*15*	*30*	*45*	*15*	*30*	*45*
	MT 2	*Alternate #1*		**MT 2**	*Choice 2*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.6*	*0.3*	*0.1*	*0.75*	*0.15*	*0.1*
Cost ($)	*250*	*500*	*750*	*100*	*200*	*300*
People	*3*	*5*	*7*	*1*	*2*	*3*
Time (days)	*30*	*45*	*60*	*5*	*10*	*15*
				MT 3	*Choice 3*	
				Fully	**Partially**	**Doesn't**
				0.65	*0.25*	*0.1*
				250	*750*	*1500*
				1	*2*	*3*
				5	*10*	*15*
				MT 4	*Choice 6*	
				Fully	**Partially**	**Doesn't**
				0.8	*0.1*	*0.1*
				0	*0*	*0*
				5	*10*	*15*
				1	*2*	*5*
	Root Cause 3			***Root Cause 4***		
	MT 1	*Choice 4*		**MT 1**	*Choice 1*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.7*	*0.2*	*0.1*	*0.7*	*0.2*	*0.1*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*1*	*2*	*3*	*2*	*3*	*5*
Time (days)	*5*	*10*	*15*	*15*	*30*	*45*
	MT 2	*Choice 5*		**MT 2**	*Choice 6*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.8*	*0.1*	*0.1*	*0.8*	*0.1*	*0.1*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*3*	*4*	*5*	*5*	*10*	*15*
Time (days)	*7*	*15*	*22*	*1*	*2*	*5*
	MT 3	*Choice 6*				
	Fully	**Partially**	**Doesn't**			
Probability	*0.6*	*0.2*	*0.2*			
Cost ($)	*0*	*0*	*0*			
People	*5*	*10*	*15*			
Time (days)	*1*	*2*	*5*			

PER RISK

	Root Cause 1			***Root Cause 2***			***Root Cause 3***		
	MT 1	*Choice 3*		**MT 1**	*Choice 1*		**MT 1**	*Choice 1*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.8*	*0.1*	*0.1*	*0.4*	*0.4*	*0.2*	*0.8*	*0.15*	*0.05*
Cost ($)	*0*	*0*	*0*	*10000*	*20000*	*30000*	*10000*	*20000*	*30000*
People	*1*	*2*	*3*	*1*	*2*	*5*	*1*	*2*	*5*
Time (days)	*2*	*5*	*7*	*0*	*7*	*15*	*0*	*7*	*15*
	MT 2	*Choice 4*		**MT 2**	*Choice 6*		**MT 2**	*Choice 2*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.5*	*0.3*	*0.2*	*0.9*	*0.05*	*0.05*	*0.8*	*0.15*	*0.05*
Cost ($)	*0*	*0*	*0*	*0*	*500*	*2500*	*0*	*0*	*0*
People	*1*	*4*	*6*	*1*	*2*	*3*	*1*	*3*	*4*
Time (days)	*5*	*15*	*22*	*1*	*2*	*5*	*1*	*2*	*5*
	MT 3	*Choice 5*		**MT 3**	*Choice 7*		**MT 3**	*Choice 4*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.3*	*0.4*	*0.3*	*0.6*	*0.2*	*0.2*	*0.5*	*0.3*	*0.2*
Cost ($)	*0*	*0*	*0*	*0*	*500*	*2500*	*0*	*0*	*0*
People	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*4*	*6*
Time (days)	*1*	*2*	*5*	*1*	*2*	*5*	*5*	*15*	*22*
	MT 4	*Choice 10*		**MT 4**	*Choice 11*		**MT 4**	*Choice 10*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.3*	*0.4*	*0.3*	*0.8*	*0.15*	*0.05*	*0.85*	*0.1*	*0.05*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
People	*1*	*4*	*6*	*1*	*2*	*3*	*1*	*3*	*4*
Time (days)	*5*	*15*	*22*	*1*	*2*	*5*	*1*	*15*	*22*

	Root Cause 4			***Root Cause 5***		
	MT 1	*Choice 1*		**MT 1**	*Choice 1*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.8*	*0.15*	*0.05*	*0.7*	*0.15*	*0.15*
Cost ($)	*10000*	*20000*	*30000*	*10000*	*20000*	*30000*
People	*1*	*2*	*5*	*1*	*2*	*5*
Time (days)	*0*	*7*	*15*	*0*	*7*	*15*
	MT 2	*Choice 3*		**MT 2**	*Choice 3*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.6*	*0.3*	*0.1*	*0.6*	*0.3*	*0.1*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*1*	*2*	*3*	*1*	*2*	*3*
Time (days)	*2*	*5*	*7*	*2*	*5*	*7*
	MT 3	*Choice 4*		**MT 3**	*Choice 4*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.7*	*0.2*	*0.1*	*0.85*	*0.1*	*0.05*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*1*	*4*	*6*	*1*	*4*	*6*
Time (days)	*5*	*15*	*22*	*5*	*15*	*22*
	MT 4	*Choice 7*		**MT 4**	*Choice 7*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.6*	*0.2*	*0.2*	*0.5*	*0.3*	*0.2*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*1*	*2*	*3*	*1*	*2*	*3*
Time (days)	*1*	*2*	*5*	*1*	*2*	*5*
	MT 5	*Choice 8*		**MT 5**	*Choice 8*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.7*	*0.2*	*0.1*	*0.5*	*0.3*	*0.2*
Cost ($)	*25*	*50*	*100*	*25*	*50*	*100*
People	*1*	*2*	*3*	*1*	*2*	*3*
Time (days)	*1*	*2*	*2*	*1*	*2*	*2*
	MT 6	*Alternate #1*		**MT 6**	*Choice 9*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.6*	*0.2*	*0.2*	*0.8*	*0.1*	*0.1*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*3*	*5*	*2*	*3*	*5*
Time (days)	*5*	*15*	*22*	*5*	*15*	*22*

COST RISK

	Root Cause 1			Root Cause 2		
	MT 1	*Choice 1*		**MT 1**	*Choice 1*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.9*	*0.05*	*0.05*	*0.2*	*0.2*	*0.6*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*1*	*2*	*3*	*1*	*2*	*3*
Time (days)	*1*	*2*	*5*	*1*	*2*	*5*
	MT 2	*Choice 2*		**MT 2**	*Choice 2*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.7*	*0.2*	*0.1*	*0.8*	*0.05*	*0.15*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*1*	*2*	*3*	*1*	*2*	*3*
Time (days)	*1*	*1*	*2*	*1*	*1*	*2*
	MT 3	*Choice 3*		**MT 3**	*Choice 3*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.8*	*0.15*	*0.05*	*0.9*	*0.1*	*0*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*1*	*2*	*3*	*1*	*2*	*3*
Time (days)	*1*	*1*	*2*	*1*	*1*	*2*
	MT 4	*Choice 4*		**MT 4**	*Choice 4*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.3*	*0.6*	*0.1*	*0.4*	*0.2*	*0.4*
Cost ($)	*50*	*100*	*250*	*50*	*100*	*250*
People	*2*	*4*	*6*	*2*	*4*	*6*
Time (days)	*2*	*7*	*15*	*2*	*7*	*15*
	MT 5	*Choice 5*		**MT 5**	*Choice 5*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.5*	*0.3*	*0.2*	*0.7*	*0.2*	*0.1*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*4*	*6*	*2*	*4*	*6*
Time (days)	*2*	*7*	*15*	*2*	*7*	*15*
	MT 6	*Choice 6*		**MT 6**	*Choice 6*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.6*	*0.2*	*0.2*	*0.8*	*0.1*	*0.1*
Cost ($)	*500*	*2500*	*5000*	*500*	*2500*	*5000*
People	*2*	*4*	*6*	*2*	*4*	*6*
Time (days)	*7*	*15*	*22*	*7*	*15*	*22*

	Root Cause 3			***Root Cause 4***		
	MT 1	*Choice 1*		**MT 1**	*Choice 1*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.2*	*0.2*	*0.6*	*0.2*	*0.2*	*0.6*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*1*	*2*	*3*	*1*	*2*	*3*
Time (days)	*1*	*2*	*5*	*1*	*2*	*5*
	MT 2	*Choice 2*		**MT 2**	*Choice 2*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.2*	*0.2*	*0.6*	*0.2*	*0.2*	*0.6*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*1*	*2*	*3*	*1*	*2*	*3*
Time (days)	*1*	*1*	*2*	*1*	*1*	*2*
	MT 3	*Choice 3*		**MT 3**	*Choice 3*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.1*	*0.8*	*0.1*	*0.1*	*0.8*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*1*	*2*	*3*	*1*	*2*	*3*
Time (days)	*1*	*1*	*2*	*1*	*1*	*2*
	MT 4	*Choice 4*		**MT 4**	*Choice 4*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.8*	*0.1*	*0.1*	*0.3*	*0.3*	*0.4*
Cost ($)	*50*	*100*	*250*	*50*	*100*	*250*
People	*2*	*4*	*6*	*2*	*4*	*6*
Time (days)	*2*	*7*	*15*	*2*	*7*	*15*
	MT 5	*Choice 5*		**MT 5**	*Choice 5*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.1*	*0.8*	*0.3*	*0.3*	*0.4*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*4*	*6*	*2*	*4*	*6*
Time (days)	*2*	*7*	*15*	*2*	*7*	*15*
	MT 6	*Choice 6*		**MT 6**	*Choice 6*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.7*	*0.2*	*0.1*	*0.7*	*0.2*	*0.1*
Cost ($)	*500*	*2500*	*5000*	*500*	*2500*	*5000*
People	*2*	*4*	*6*	*2*	*4*	*6*
Time (days)	*7*	*15*	*22*	*7*	*15*	*22*

PREFERENCE SYSTEM

	Gamma	**K**	0
Time	0.1	**K1**	0.8
Cost	0.002	**K2**	0.7
People	0.5	**K3**	0.7

Appendix D: Operations Life Cycle Phase Data

Recall that the highlighted values represent values changed from the testing life cycle phase from Appendix C.

PAYLOAD RISK

	Root Cause 1			Root Cause 2		
	MT 3	*Choice 3*		**MT 3**	*Choice 3*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.6*	*0.2*	*0.2*	*0.85*	*0.1*	*0.05*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*4*	*6*	*2*	*4*	*6*
Time (days)	*2*	*7*	*11*	*2*	*7*	*11*
	MT 4	*Choice 4*		**MT 4**	*Choice 4*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.75*	*0.15*	*0.1*	*0.9*	*0.05*	*0.05*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*4*	*6*	*2*	*4*	*6*
Time (days)	*2*	*7*	*11*	*2*	*7*	*11*
	MT 5	*Choice 5*		**MT 5**	*Choice 5*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.75*	*0.15*	*0.1*	*0.6*	*0.3*	*0.1*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*4*	*6*	*2*	*4*	*6*
Time (days)	*2*	*7*	*11*	*2*	*7*	*11*

	Root Cause 3			Root Cause 4		
	MT 3	*Choice 3*		**MT 3**	*Choice 2*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.4*	*0.3*	*0.3*	*0.5*	*0.2*	*0.3*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*4*	*6*	*2*	*4*	*6*
Time (days)	*2*	*7*	*11*	*2*	*7*	*11*
	MT 4	*Choice 4*		**MT 4**	*Choice 4*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.4*	*0.3*	*0.3*	*0.5*	*0.2*	*0.3*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*4*	*6*	*2*	*4*	*6*
Time (days)	*2*	*7*	*11*	*2*	*7*	*11*
	MT 5	*Choice 5*		**MT 5**	*Choice 5*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.9*	*0.05*	*0.05*	*0.9*	*0.05*	*0.05*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*4*	*6*	*2*	*4*	*6*
Time (days)	*2*	*7*	*11*	*2*	*7*	*11*

SC1 RISK

	Root Cause 1			***Root Cause 2***			***Root Cause 3***		
	MT 2	*Choice 7*		**MT 2**	*Choice 3*		**MT 2**	*Choice 3*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.9*	*0.05*	*0.05*	*0.75*	*0.15*	*0.1*	*0.9*	*0.05*	*0.05*
Cost ($)	*0*	*1250*	*1725*	*0*	*0*	*0*	*0*	*0*	*0*
People	*1*	*2*	*4*	*2*	*3*	*5*	*2*	*3*	*5*
Time (days)	*3*	*7*	*15*	*1*	*2*	*3*	*1*	*2*	*3*
				MT 3	*Choice 4*		**MT 3**	*Choice 4*	
				Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability				*0.8*	*0.1*	*0.1*	*0.8*	*0.1*	*0.1*
Cost ($)				*0*	*0*	*0*	*0*	*0*	*0*
People				*2*	*3*	*5*	*2*	*3*	*5*
Time (days)				*1*	*2*	*3*	*1*	*2*	*3*
				MT 4	*Choice 5*		**MT 3**	*Choice 4*	
				Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability				*0.9*	*0.05*	*0.05*	*0.75*	*0.15*	*0.1*
Cost ($)				*0*	*0*	*0*	*0*	*0*	*0*
People				*2*	*3*	*5*	*2*	*3*	*5*
Time (days)				*1*	*2*	*3*	*1*	*2*	*3*
				MT 5	*Choice 6*		**MT 5**	*Choice 6*	
				Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability				*0.9*	*0.05*	*0.05*	*0.9*	*0.05*	*0.05*
Cost ($)				*0*	*0*	*0*	*0*	*0*	*0*
People				*1*	*2*	*3*	*1*	*2*	*3*
Time (days)				*2*	*3*	*5*	*2*	*3*	*5*
				MT 6	*Choice 8*		**MT 6**	*Choice 8*	
				Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability				*0.7*	*0.2*	*0.1*	*0.8*	*0.1*	*0.1*
Cost ($)				*0*	*0*	*0*	*0*	*0*	*0*
People				*1*	*2*	*3*	*1*	*2*	*3*
Time (days)				*2*	*3*	*5*	*2*	*3*	*5*

	Root Cause 4			***Root Cause 5***		
	MT 2	*Choice 3*		**MT 2**	*Choice 3*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.75*	*0.15*	*0.1*	*0.85*	*0.05*	*0.1*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*3*	*5*	*2*	*3*	*5*
Time (days)	*1*	*2*	*3*	*1*	*2*	*3*
	MT 3	*Choice 4*		**MT 3**	*Choice 4*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.8*	*0.1*	*0.1*	*0.8*	*0.1*	*0.1*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*3*	*5*	*2*	*3*	*5*
Time (days)	*1*	*2*	*3*	*1*	*2*	*3*
	MT 4	*Choice 5*		**MT 4**	*Choice 5*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.9*	*0.05*	*0.05*	*0.9*	*0.05*	*0.05*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*3*	*5*	*2*	*3*	*5*
Time (days)	*1*	*2*	*3*	*1*	*2*	*3*
	MT 5	*Choice 6*		**MT 5**	*Choice 6*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.9*	*0.05*	*0.05*	*0.9*	*0.05*	*0.05*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*1*	*2*	*3*	*1*	*2*	*3*
Time (days)	*2*	*3*	*5*	*2*	*3*	*5*
	MT 6	*Choice 8*		**MT 6**	*Choice 8*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.9*	*0.05*	*0.05*	*0.75*	*0.15*	*0.1*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*1*	*2*	*3*	*1*	*2*	*3*
Time (days)	*2*	*3*	*5*	*2*	*3*	*5*

SC2 RISK

	Root Cause 1			***Root Cause 2***			***Root Cause 3***		
	MT 1	*Choice 1*		**MT 1**	*Choice 1*		**MT 1**	*Choice 1*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.7*	*0.2*	*0.1*	*0.7*	*0.2*	*0.1*	*0.7*	*0.2*	*0.1*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
People	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*
Time (days)	*1*	*2*	*3*	*1*	*7*	*15*	*1*	*15*	*45*
	MT 2	*Choice 2*		**MT 2**	*Choice 2*		**MT 2**	*Choice 2*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.8*	*0.1*	*0.1*	*0.8*	*0.1*	*0.1*	*0.8*	*0.1*	*0.1*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*4*	*5*	*2*	*4*	*5*	*2*	*4*	*5*
Time (days)	*2*	*5*	*7*	*2*	*7*	*15*	*2*	*15*	*45*
	MT 3	*Choice 3*		**MT 3**	*Choice 3*		**MT 3**	*Choice 3*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.9*	*0.05*	*0.05*	*0.9*	*0.05*	*0.05*	*0.9*	*0.05*	*0.05*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
People	*3*	*6*	*7*	*3*	*6*	*7*	*3*	*6*	*7*
Time (days)	*3*	*7*	*11*	*3*	*7*	*15*	*3*	*15*	*45*
	MT 4	*Choice 6*		**MT 4**	*Choice 7*		**MT 4**	*Choice 7*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.9*	*0.05*	*0.05*	*0.9*	*0.05*	*0.05*	*0.9*	*0.05*	*0.05*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*4*	*5*	*2*	*4*	*5*	*2*	*4*	*5*
Time (days)	*2*	*5*	*7*	*3*	*7*	*15*	*3*	*15*	*45*
	MT 5	*Choice 7*							
	Fully	**Partially**	**Doesn't**						
Probability	*0.9*	*0.05*	*0.05*						
Cost ($)	*0*	*0*	*0*						
People	*2*	*4*	*5*						
Time (days)	*2*	*5*	*7*						

	Root Cause 4			Root Cause 5		
	MT 1	*Choice 1*		**MT 1**	*Choice 1*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.7*	*0.2*	*0.1*	*0.7*	*0.2*	*0.1*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*1*	*2*	*3*	*1*	*2*	*3*
Time (days)	*1*	*3*	*10*	*1*	*3*	*22*
	MT 2	*Choice 2*		**MT 2**	*Choice 2*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.8*	*0.1*	*0.1*	*0.8*	*0.1*	*0.1*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*4*	*5*	*2*	*4*	*5*
Time (days)	*1*	*3*	*10*	*1*	*3*	*22*
	MT 3	*Choice 3*		**MT 3**	*Choice 3*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.9*	*0.05*	*0.05*	*0.9*	*0.05*	*0.05*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*3*	*6*	*7*	*3*	*6*	*7*
Time (days)	*1*	*3*	*10*	*1*	*3*	*22*
	MT 4	*Choice 7*		**MT 4**	*Choice 7*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.9*	*0.05*	*0.05*	*0.9*	*0.05*	*0.05*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*4*	*5*	*2*	*4*	*5*
Time (days)	*2*	*3*	*10*	*1*	*3*	*22*
	MT 5	*Choice 9*		**MT 5**	*Choice 9*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.9*	*0.05*	*0.05*	*0.9*	*0.05*	*0.05*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*1*	*2*	*3*	*1*	*2*	*3*
Time (days)	*1*	*3*	*10*	*1*	*3*	*22*

	Root Cause 6			***Root Cause 7***		
	MT 1	*Choice 7*		**MT 1**	*Choice 12*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.75*	*0.15*	*0.1*	*0.9*	*0.05*	*0.05*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*4*	*5*	*4*	*8*	*12*
Time (days)	*1*	*3*	*7*	*2*	*7*	*15*
	MT 2	*Choice 12*		**MT 2**	*Choice 14*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.9*	*0.05*	*0.05*	*0.85*	*0.1*	*0.05*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*4*	*8*	*12*	*2*	*4*	*5*
Time (days)	*2*	*7*	*15*	*2*	*7*	*15*
	MT 3	*Choice 13*		**MT 3**	*Choice 16*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.85*	*0.1*	*0.05*	*0.8*	*0.1*	*0.1*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*4*	*5*	*2*	*3*	*4*
Time (days)	*2*	*7*	*15*	*7*	*15*	*22*
	MT 4	*Choice 15*				
	Fully	**Partially**	**Doesn't**			
Probability	*0.8*	*0.1*	*0.1*			
Cost ($)	*0*	*0*	*0*			
People	*2*	*3*	*4*			
Time (days)	*7*	*15*	*22*			
	MT 5	*Choice 3*				
	Fully	**Partially**	**Doesn't**			
Probability	*0.75*	*0.15*	*0.1*			
Cost ($)	*0*	*0*	*0*			
People	*1*	*2*	*4*			
Time (days)	*2*	*3*	*7*			

SC3 RISK

	Root Cause 1			***Root Cause 2***		
	MT 1	*Choice 1*		**MT 1**	*Choice 1*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.9*	*0.05*	*0.05*	*0.9*	*0.05*	*0.05*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*3*	*5*	*2*	*3*	*5*
Time (days)	*7*	*15*	*22*	*7*	*15*	*22*
				MT 4	*Choice 6*	
				Fully	**Partially**	**Doesn't**
Probability				*0.9*	*0.05*	*0.05*
Cost ($)				*0*	*0*	*0*
People				*5*	*10*	*15*
Time (days)				*1*	*2*	*5*

	Root Cause 3			***Root Cause 4***		
	MT 1	*Choice 4*		**MT 1**	*Choice 1*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.8*	*0.1*	*0.1*	*0.8*	*0.1*	*0.1*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*1*	*2*	*3*	*2*	*3*	*5*
Time (days)	*2*	*5*	*7*	*7*	*15*	*22*
	MT 2	*Choice 5*		**MT 2**	*Choice 6*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.9*	*0.05*	*0.05*	*0.9*	*0.05*	*0.05*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*3*	*4*	*5*	*5*	*10*	*15*
Time (days)	*3*	*7*	*11*	*1*	*2*	*5*
	MT 3	*Choice 6*				
	Fully	**Partially**	**Doesn't**			
Probability	*0.7*	*0.1*	*0.2*			
Cost ($)	*0*	*0*	*0*			
People	*5*	*10*	*15*			
Time (days)	*1*	*2*	*5*			

PER RISK

	Root Cause 1			***Root Cause 2***			***Root Cause 3***		
	MT 1	*Choice 3*		**MT 1**	*Choice 1*		**MT 1**	*Choice 1*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.9*	*0.05*	*0.05*	*0.5*	*0.3*	*0.2*	*0.9*	*0.05*	*0.05*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
People	*1*	*2*	*3*	*1*	*2*	*5*	*1*	*2*	*5*
Time (days)	*1*	*2*	*3*	*0*	*3*	*7*	*0*	*3*	*7*
	MT 2	*Choice 4*		**MT 2**	*Choice 6*		**MT 2**	*Choice 2*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.6*	*0.2*	*0.2*	*0.9*	*0.05*	*0.05*	*0.9*	*0.05*	*0.05*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
People	*1*	*4*	*6*	*1*	*2*	*3*	*1*	*3*	*4*
Time (days)	*2*	*7*	*11*	*1*	*2*	*5*	*1*	*2*	*5*
	MT 3	*Choice 5*		**MT 3**	*Choice 7*		**MT 3**	*Choice 4*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.4*	*0.3*	*0.3*	*0.7*	*0.1*	*0.2*	*0.6*	*0.2*	*0.2*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
People	*1*	*2*	*3*	*1*	*2*	*3*	*1*	*4*	*6*
Time (days)	*1*	*2*	*5*	*1*	*2*	*5*	*2*	*7*	*11*
	MT 4	*Choice 10*		**MT 4**	*Choice 11*		**MT 4**	*Choice 10*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.4*	*0.3*	*0.3*	*0.9*	*0.05*	*0.05*	*0.9*	*0.05*	*0.05*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
People	*1*	*4*	*6*	*1*	*2*	*3*	*1*	*3*	*4*
Time (days)	*2*	*7*	*11*	*1*	*2*	*5*	*1*	*7*	*11*

	Root Cause 4			*Root Cause 5*		
	MT 1	*Choice 1*		**MT 1**	*Choice 1*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.9*	*0.05*	*0.05*	*0.8*	*0.1*	*0.1*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*1*	*2*	*5*	*1*	*2*	*5*
Time (days)	*0*	*3*	*7*	*0*	*3*	*7*
	MT 2	*Choice 3*		**MT 2**	*Choice 3*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.7*	*0.2*	*0.1*	*0.7*	*0.2*	*0.1*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*1*	*2*	*3*	*1*	*2*	*3*
Time (days)	*1*	*2*	*3*	*1*	*2*	*3*
	MT 3	*Choice 4*		**MT 3**	*Choice 4*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.8*	*0.1*	*0.1*	*0.9*	*0.05*	*0.05*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*1*	*4*	*6*	*1*	*4*	*6*
Time (days)	*2*	*7*	*11*	*2*	*7*	*11*
	MT 4	*Choice 7*		**MT 4**	*Choice 7*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.7*	*0.2*	*0.1*	*0.6*	*0.2*	*0.2*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*1*	*2*	*3*	*1*	*2*	*3*
Time (days)	*1*	*2*	*5*	*1*	*2*	*5*
	MT 5	*Choice 8*		**MT 5**	*Choice 8*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.8*	*0.1*	*0.1*	*0.6*	*0.2*	*0.2*
Cost ($)	*25*	*50*	*100*	*25*	*50*	*100*
People	*1*	*2*	*3*	*1*	*2*	*3*
Time (days)	*1*	*2*	*2*	*1*	*2*	*2*
	MT 6	*Alternate #1*		**MT 6**	*Choice 9*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.7*	*0.1*	*0.2*	*0.9*	*0.05*	*0.05*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*3*	*5*	*2*	*3*	*5*
Time (days)	*2*	*7*	*11*	*5*	*15*	*22*

COST RISK

	Root Cause 1			*Root Cause 2*		
	MT 1	*Choice 1*		**MT 1**	*Choice 1*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.9*	*0.05*	*0.05*	*0.2*	*0.2*	*0.6*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*1*	*2*	*3*	*1*	*2*	*3*
Time (days)	*1*	*2*	*5*	*1*	*2*	*5*
	MT 2	*Choice 2*		**MT 2**	*Choice 2*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.8*	*0.1*	*0.1*	*0.8*	*0.05*	*0.15*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*1*	*2*	*3*	*1*	*2*	*3*
Time (days)	*1*	*1*	*2*	*1*	*1*	*2*
	MT 3	*Choice 3*		**MT 3**	*Choice 3*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.9*	*0.05*	*0.05*	*0.9*	*0.1*	*0*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*1*	*2*	*3*	*1*	*2*	*3*
Time (days)	*1*	*1*	*2*	*1*	*1*	*2*
	MT 6	*Choice 6*		**MT 6**	*Choice 6*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.7*	*0.1*	*0.2*	*0.8*	*0.1*	*0.1*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*4*	*6*	*2*	*4*	*6*
Time (days)	*3*	*7*	*11*	*3*	*7*	*11*

	Root Cause 3			*Root Cause 4*		
	MT 1	*Choice 1*		**MT 1**	*Choice 1*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.2*	*0.2*	*0.6*	*0.2*	*0.2*	*0.6*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*1*	*2*	*3*	*1*	*2*	*3*
Time (days)	*1*	*2*	*5*	*1*	*2*	*5*
	MT 2	*Choice 2*		**MT 2**	*Choice 2*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.2*	*0.2*	*0.6*	*0.2*	*0.2*	*0.6*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*1*	*2*	*3*	*1*	*2*	*3*
Time (days)	*1*	*1*	*2*	*1*	*1*	*2*
	MT 3	*Choice 3*		**MT 3**	*Choice 3*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.1*	*0.1*	*0.8*	*0.1*	*0.1*	*0.8*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*1*	*2*	*3*	*1*	*2*	*3*
Time (days)	*1*	*1*	*2*	*1*	*1*	*2*
	MT 6	*Choice 6*		**MT 6**	*Choice 6*	
	Fully	**Partially**	**Doesn't**	**Fully**	**Partially**	**Doesn't**
Probability	*0.8*	*0.1*	*0.1*	*0.8*	*0.1*	*0.1*
Cost ($)	*0*	*0*	*0*	*0*	*0*	*0*
People	*2*	*4*	*6*	*2*	*4*	*6*
Time (days)	*3*	*7*	*11*	*3*	*7*	*11*

PREFERENCE SYSTEM

	Gamma	**K**	0
Time	0.1	**K1**	0.95
Cost	0.002	**K2**	0.7
People	0.5	**K3**	0.9

Glossary

ANOVA	Analysis of Variation
ARMADILLO	Atmosphere Related Measurements And Detection of submILLimeter Objects
CER	Cost Estimating Relationship
Certain equivalent	Amount of worth received for certain such that the decision-maker is indifferent between receiving the amount and participating in the lottery.
CqER	Consequence Estimating Relationship
CubeSats	Satellites in the shape of 10x10x10 centimeter (1U) cubes; multiple units may be combined to form larger spacecraft.
Decision tree	A set of prospects with associated probabilities (also called lotteries)
Decision tree	An irrevocable allocation of resources.
Decision-maker	An individual (group of people or single person) who has the power to commit the resources of the organization
DoD	Department of Defense
DRAGON	Dual Radio Frequency Astrodynamic GPS Orbital Navigator
FASTRAC	Formation Autonomy Spacecraft with Thrust, RelNav, Attitude, and Crosslink
FOI	Factors of Interest
GER	General Error Regression
GPS	Global Positioning System
INSPIRE	Interplanetary NanoSpacecraft Pathfinder In a Relevant Environment
IRLS	Iteratively Reweighted Least Squares
JPL	Jet Propulsion Lab
L-C	Likelihood-Consequence
LEO	Low Earth Orbit
LER	Likelihood Estimating Relationship

LONESTAR	Low Earth Orbiting Navigation Experiment for Spacecraft Testing Autonomous Rendezvous and docking
MPE	Minimum Percentage Error
MUPE	Minimum Unbiased Percentage Error
OLS	Ordinary Least Squares
PDD	Piezo-electric Dust Detector
Probability	A belief that an event will occur
RACE	Radiometer Atmosphere CubeSat Experiment
RER	Risk Estimating Relationship
Risk mitigation	An option that best provides the balance between performance and cost to reduce the mission risk likelihood and/or consequence
Risk preference	The level of preference, indifference, or aversion to taking risks.
SEE	Standard Error of the Estimate
Small satellite	Spacecraft with a mass of less than 100 kilograms
SSCM	Small Satellite Cost Model
SSD	Sum of Squared Deviations
TEC	Total Electron Content
TSL	Texas Spacecraft Laboratory
UNP	University Nanosatellite Program
USCM	Unmanned Spacecraft Cost Model
UT-Austin	The University of Texas at Austin
VBA	Visual Basics for Applications
ZPB-MPE	Zero Percentage Bias, Minimum Percentage Error

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Vita

Katharine was born in Burnsville, MN. After graduating from Apple Valley High School in 2006, she attended Purdue University to study Aeronautical/Astronautical Engineering. During her undergraduate career, Katharine interned for The Aerospace Corporation and The Boeing Company working on missions ranging from Air Force launches to the Space Shuttle and International Space Station. In May 2010, Katharine received the degree of Bachelor of Science in Aeronautical/Astronautical Engineering with a minor in Mathematics and moved to Austin, Texas to continue her study of Aerospace Engineering at the University of Texas at Austin.

Katharine discovered the topic of this dissertation while working in the Texas Spacecraft Laboratory as the lead systems engineer for all the missions as well as the student program manager for the ARMADILLO satellite. As manager, she led the team through a two year competition cycle, ultimately winning the CubeSat class award at the University Nanosatellite Program in January 2013.

During her time at UT-Austin, Katharine has been funded by various positions including: Teaching Assistant, Research Assistant, and a combination of the two. She became a National Defense Science and Engineering Graduate fellow starting in September 2013.

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