DESIGN TEAMS, COMPLEX SYSTEMS AND UNCERTAINTY

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ABSTRACT

The design process can be viewed as a series of actions for reducing uncertainty in product or system design specifications. At the beginning of the design process, the uncertainty is high because the design space has yet to be explored and decisions have not been made. This uncertainty contributes to *design risk*, risk due to the engineer's lack of knowledge and/or information. In design teams, design risk takes on the added dimension of lack of group awareness about the state of knowledge of each of the team member. To better understand and capture uncertainty inherent in early design, we have developed a methodology to model design evolution in concurrent design teams. The representation is a directed graph that represents the state of a design over time. In this paper we describe our modeling methodology and present a case study of two different design teams. We present the results of modeling a part of the design process. Then we show how the model can be analyzed for understanding how information and knowledge transfer was used to make decisions and reduce uncertainty and design risk.

KEYWORDS

risk-based design, concurrent engineering, design team support, design theory and methodology, design activity

1 INTRODUCTION

The design process can be viewed as a series of tasks and decisions for reducing uncertainty. At the beginning of the design process uncertainty is high since no one knows how the design will be realized or what its true performance will be. Uncertainty can be associated with having multiple alternatives to choose from. Before an alternative is selected, it is difficult to predict with any certainty how the final product will perform. Deciding which alternative to take reduces this type of uncertainty. Uncertainty also arises from lack of the knowledge needed to develop alternatives in the first place. Part of the designer's task is to come up with and investigate available alternatives. Finally, uncertainty can be associated with the lack of information or knowledge required to make a good selection. Gathering and analyzing the information needed to make decisions is also part of the designer's task.

This uncertainty is not necessarily negative. The uncertainty associated with having multiple alternatives is often useful. Indeed, as the designers gain knowledge, they may use it to develop new alternatives which increases uncertainty. Especially during the early stages of design it is desirable to explore as much of the design space as possible.

Uncertainty becomes negative when it causes inefficiencies in the design process or results in poor decision-making. A designer's lack of knowledge may cause them to narrow down to a single concept too early and to select a poor alternative. A bad choice early in the design may turn out to be infeasible as the design progresses, or it may result in an overly complex and costly design. Negative uncertainty contributes to *design risk*, the risk associated with lack of knowledge. The concept of design risk is a recently developed idea and definitions vary. We use the definition introduced in [1]—design risk is risk due to lack of knowledge. This risk comes into play during the design process, as design engineers and managers make decisions about how to proceed with the design and where to put their resources. There is a risk that they may not have enough information to make good decisions. This risk no longer exists once the design is complete.

In design teams, design risk takes on added dimensions since knowledge is distributed throughout the team. A designer working alone is at all times aware of the current state of the design, the available alternatives, their progress on design tasks, and the results from each task. The designer can gain knowledge through researching external sources and performing analyses. In contrast, a team working on a complex product or system design will divide the design responsibilities among the team members, often by decomposing the product into subsystems. A team manager or systems engineer keeps track of the current state of the design, but other team members may not maintain this awareness. Even more problematic, a team member's design tasks and decisions will likely be dependent on those of other team members. The information that a team member needs to make good decisions may need to come from another team member. Poor communication and situation awareness may inhibit the efficient flow of information. Negative uncertainty arises from team members proceeding with tasks or decisions using inaccurate or outdated knowledge of the state of other parts of the design.

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Using collaborative engineering support applications is one method for facilitating information flow information within a team. These applications can be ad hoc, such as when teams agree to use email and document sharing applications to share information. Or the application can be more specific, such as database applications designed to track design changes using a formal protocol.

Designing these support applications requires understanding how information is used and communicated within teams. In our work, we are interested in concurrent engineering teams designing complex systems. In complex integrated systems, it is impossible to decompose the system such that each of the subsystems can be designed independently. Decisions made for one subsystem may critically affect the alternatives available for another subsystem as well as the performance of the whole system. Decisions also affect the flow of the design process. With better decisions, more of the design space can be explored and expensive redesigns are reduced. During the design process, uncertainty cannot be fully eliminated since communication is not instantaneous, and team members must often proceed without waiting on decisions being made by others. We believe that understanding how the level of uncertainty and design risk is affected by communication and information flow will provide insights into how to design collaborative software for concurrent engineering teams.

We have developed a methodology to model design decision-making and information flow over time. The representation is a flow diagram. The diagram elements with elements to represent levels of uncertainty, decisions points, information flow and uncertainty reducing tasks. The goal of our work is to identify opportunities for improving the design process through facilitating team communication and group awareness.

In this paper we describe our modeling methodology and present a case study of two space mission design teams. We present the results of modeling a part of the design process of each of these teams. We show how the model can be analyzed to understand **Error! Reference source not found.**team strategies for reducing uncertainty. We identify problem areas where information flow and situation awareness are impeded.

2 MOTIVATION AND BACKGROUND

Our study of uncertainty in the design process is motivated by the complexity of space mission design. The missions designed by NASA require the effort and knowledge of teams of engineers. Because NASA missions are high-risk and high cost enterprises, developing methods and tools to facilitate rational decision making is a continuing challenge for NASA. The complexity of the missions results in high uncertainty when making decisions and performing design tasks.

2.1 Space mission design teams

Traditionally, space mission systems are decomposed into separate mission functions that are closely matched with specific physical (or software) assemblies and structures. The mission design team is then organized into subsystem experts who are responsible for the design of the subsystems within their functional of disciplinary area and systems engineers who are responsible for integrating the system as a whole. Depending on the mission, space mission system will typically include the subsystems propulsion, power, structures and mechanisms, communications, attitude determination and control, command and data handling, thermal control, and ground systems.

Though mission designers have found a way to break down the design problem into smaller problems, the subsystems remain tightly coupled. For instance, the propulsion and attitude control subsystems may belong to different engineering subsystems, but they must be designed concurrently since propulsion is used to control attitude and the attitude control architecture places constraints on the propulsion design. Decisions made in one subsystem have significant ramifications for other subsystems as well for as the mission system design as a whole.

2.2 Risk-based design at NASA

Over the last twenty years, NASA has been developing processes for incorporating risk management into the project lifecycle. Qualitative assessment and tracking of risks using so-called fever charts is ubiquitous. Reliability-based methods, such as failure modes and effects analysis (FMEA) and fault tree analysis (FTA) are standard practice and can be used to identify design problems throughout the design process. A major shortcoming of these methods is that they do not provide a *systematic* method for allocating methods to reduce risk. In the mid-nineties NASA began investigating the use of probabilistic risk assessment (PRA) in mission design [2]. The idea was that the quantification of risk could be used to define and measure acceptable levels of risk, calculate the cost of reducing risk, and optimize the balance of cost versus risk [11]. One of the early efforts was the first PRA performed on the space shuttle design in 1996. Work continues on developing methods to use PRA to make design choices, and the proper application of PRA during design is still being debated especially because the numbers in calculating probabilities are difficult to justify. Even when the appropriateness of the probabilities are well established, design engineers have difficulty incorporating risk into their design decision [5]. This is partly due to the difficulty of determining the relationship between subsystem design changes and system level effects.

NASA has developed a number of ways to manage uncertainty. For example, the subsystem designers refer to a technology's maturity by noting its *Technology Readiness Level* (TRL). The TRL describes the uncertainty in the successful realization of the proposed technology as a numerical value between 1 and 9. (The lower the TRL, the higher the uncertainty in any evaluation associated with the system). *Design margin*, as designated by a predefined percentage, is used to characterize uncertainty in design parameter values. At NASA, the design margins are usually dictated by the design phase. During

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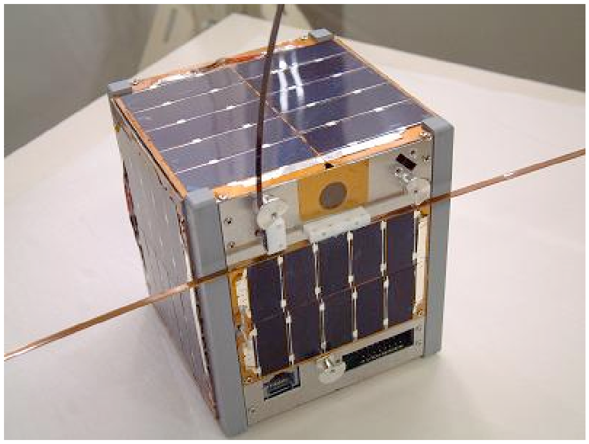

Figure 1: A typical Cubesat, measuring 12 cm. per side. (Design from the University of Tokyo.)

conceptual design, the margin starts out as high as 40 percent. As the design passes through different phase gates, the design margin gets "consumed." Design margin is also referred to as *contingency.*"

Early phases of mission design are particularly problematic since the uncertainty is so high. The design is mainly conceptual and there is very little hard information on which to base decisions. In recent years, NASA has been developing methods and tools for use during early stage design. Meshkat et al [4] developed a qualitative risk assessment tool that is in use by a conceptual mission design teams. The tool provides a collaborative interface to collect subsystem risks and aggregate them into a system level view of the design's risk using a fever chart. Van Wie et al [5] has looked at the communication of risk-elements in a concurrent engineering design team. That work lead to a linguistics based prescriptive process for communicating risk. Stone et al [6] and Tumer et al [7,8] developed a method directed at the conceptual design phase to identify potential functional failures.

3 KATYSAT TEAM STUDY

The second field study we present is of a student design team from a Stanford University graduate spacecraft design class [9]. The main objective of this field study was to record examples of alternative selection decision points that were addressed by the team or by individual engineers. In addition to recording the trade study information, we also wanted to collect examples of sources of uncertainty that arose during the design activities.

In these classes, most of the students are professional aerospace engineers though some are graduate students. Project teams have nine months to design, build and test the hardware and software for a space mission system. Working with one of these teams gave us an opportunity to study design tasks and decision-making at the more detailed design levels. The class lasts for three quarters. The first quarter consists of formal lectures and labs in which students learn systems engineering and the design and analysis of key mission subsystems. During the 2nd quarter, the class divides up into project teams, and each team selects a mission. The students develop design requirements, perform trade studies and start to build prototype components and assemblies. The final quarter is for final development, build and testing. Many of the teams get to see their spacecraft deployed if their design is successful and they raise enough money to afford payload space on a scheduled launch.

We began our study of the KatySat design team in the middle of the 2nd quarter when they had just completed their system requirements review. For the next four months, we followed the project's progress through their preliminary design review. Their next major milestone was building the "engineering model", a fully integrated and assembled prototype of their spacecraft design.

3.1 Background

The task of this nine-person design team was to conceive, design and implement a satellite mission system that they named KatySat. In the KatySat mission concept, the satellite is designed for use by high school students. At participating schools, students use the internet to communicate with the satellite via a Stanford University ground station. A 6 meter dish at the ground station enables high bandwidth links. Low bandwidth links to ham band radios and handheld antennas allow students to communicate with the satellite directly. Possible communications include sending commands to the satellite, receiving satellite telemetry, and uploading and downloading multimedia files.

The satellite design is based on the Cubesat standard. A Cubesat is a picosatellite [11], weighing less than one kilogram and designed to fit in a cubic structure that is 12 cm on a side. These types of satellite have a lifetime of several years. Figure 1 shows a typical cubesat from a previous project. Solar arrays and antennae are mounted directly to the satellite frame.

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The KatySat team is organized around mission subsystems. In addition, one student takes on the role of program manager and another is responsible for requirements. Each “design engineer” on the team leads a subsystem design. (We use the term *subsystem* to refer loosely to subsystems and disciplines.) The main hardware subsystems are electrical power system, command and data handling, and payload communications. Smaller satellite elements are grouped together into a subsystem called Systems Integrations (SI). SI is a catchall of system engineering as well as design and analysis tasks for structures, attitude determination, as well as orbit, thermal and environmental analysis. The software subsystems are the Ground Systems Architecture (which includes the mission operations and payload user applications) and the System Status and Health Analysis System tools. In addition, the team has other mission development responsibilities such as launch procurement and requirements development. **Table 1** lists the main subsystems or project roles.

Table 1. Mission subsystems and project roles.

Subsystem
Electrical Power System
Command and Data Handling
Payload Communications
Systems Integration
Ground Systems Architecture
Systems Status and Health Analysis
Program Manager
Requirements Manager

The class itself officially met two times a week. At this point in the class, the time was used for engineering design and analysis activities. Some of the time was used for formal meetings with the entire team to provide updates on the status of their work, or to present issues for the team to discuss as a whole. For instance, the team met to review the power requirements for each of the subsystems when the power distribution lead was putting together the system power budget. The rest of the time was used as lab time for the engineers to work on their tasks individually.

3.2 Field Study Methodology

Our data sources included qualitative interviews, observation with informal and semi-formal notetaking, formal and informal design documents, the KatySat project management website and the project educational website [12]. We had the same access to their project management site as did their project mentors—volunteers from the local aerospace community who advised them and acted as a design review board.) The design artifacts we collected included formal presentation slides such as the System Requirements Review presentation, structured documents, such as the power budget or communications budget tables, block diagrams, and informal documents, such as email exchanges.

At the start of the study we familiarized ourselves with the design problem, the CubeSat technologies, the organization of the design team, and some of the major decisions that had already been made. The class instructor provided this background information during initial interviews. He also provided us with some reference and design documents. We reviewed all of this information before meeting with the design team.

We conducted observations by visiting the team weekly or biweekly during their scheduled class meeting times. We also used this time for interviewing individual team members to follow up on specific design problems. During some interivews we asked the student to provide explicit information about their current trade studies and decision points.

We recorded every instance in which the team was considering design alternatives regardless of whether they performed a formal decision-making process. To identify decision points we first asked the team to identify trade studies since trade studies are a formal, and therefore explicit, type of decision-making. For these trade studies, the students could provide documents of trade tables and decision matrices. From these documents we could identify the design alternatives, the selection criteria and the team’s evaluation of each alternative. We found other decision points through reviewing informal design documents where design alternatives were listed but the format was not a full decision matrix: different architectures for the spacecraft bus, options for battery technologies, alternative antennae designs, etc. We also inferred what other decisions might be through a combination of observations, interviews and our own engineering knowledge. In these cases we would follow up with one of the engineers to confirm that these decisions were part of their design tasks.

For each trade we documented the nature of the trade in narrative form, and the idemtified the decision-making elements to the extent possible. The decision elements we recorded are shown in **Table** 2.

Table 2: Decision elements.

Decision Element	**Description**
Design problem	A textual description of the design context under which the decision is made.
Alternatives	A list of the alternatives under consideration.
Criteria	A list of parameters used as criteria to select the best alternative.
Criteria target	The target values for the criteria.
Criteria values	Estimated value for the criteria

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Subsystem interactions	A list of the subsystems that would be affected by the decision outcome.
Outcome	The alternative that was finally selected.

3.3 Selected observations

We present our observations of the decision points, design tasks, sources of uncertainty and overall design evolution of two different KatySat subsystems. In the descriptions below, we will sometimes refer to the subsystem lead engineers by the names of their respective subsystems. For instance, we will refer to the lead designer for the electrical power system as EPS, the lead for payload communications as Comm.

Design evolution of electrical power system

The power subsystem generates, stores and supplies electrical power to the rest of the satellite's electronic components. In the KatySat design, electrical power is generated by solar arrays mounted to the sides of the cube structure and then stored in onboard batteries. Although the EPS is referred to as a subsystem, the design requires systems engineering problem-solving since power is used by almost all of the other onboard subsystems.

One of the systems level design tasks for the EPS lead is power budget specification. The power budget flows down the amount of power that will be provided to each subsystem, effectively creating a design constraint for each subsystem. At the same time, the power needs of each subsystem create performance targets for the power system. Early in the design process, the power needs are not completely known since components for the rest of the subsystems are still being selected.

The initial power budget was developed during a group meeting where the team compiled information on power needs. The program manager and the EPS lead engineer went around the room asking each subsystem to list their bill of materials and component specifications. This information was organized into a matrix listing all of the spacecraft's electronic components, the power modes of the spacecraft, and the power needs of each component during the different modes. At this point, the actual power needs are uncertain because the component selections are not finalized. During one discussion, the project manager asks the engineers what kind of memory they will use if they decide to put a camera on the satellite..

In these early power budget discussions, we also observed cases of the team bringing up risk and uncertainty due to potential failures. Some of the failures modes are brought up by the professor who has depth of experience in developing cubesats. In the initial meeting, he brings up the risk of the battery running down, the risk of a component on board burns out due to "latch up" in the electrical distribution system, and the possibility that the batteries lose efficiency if they get too cold. In this case, risk was identified because of the professor's expertise. More potential failures are discussed in later meetings.

The team carries out design tasks to manage the uncertainty due to potential failures, the team investigates the criticality of the failures and acceptability of risks due to failure. In the case of the "latch up" problem, they decide that this is an acceptable risk. They also examine the potential causes of failures. One cause is environmental. None of the batteries are space rated, so the team does not know how the thermal and vacuum flight environment will affect battery performance. They to do more research on the batter performance characteristics determine if cold is in fact a problem.

Following PDR, the team discusses the need for *contingency* in the power budgets. Specifying contingency levels is another way they manage uncertainty. The program manager tells the power subsystem lead to have a 30 percent contingency and tells the rest of the subsystem leads to plan on 25 percent less power than they were budgeted

The issue of the batteries' susceptibility to cold illustrates how decisions for one subsystem ripple into design constraints for other subsystems. There are several alternatives for controlling battery temperature, and each alternative creates more alternative designs for other subsystems. For instance, the teams lays out three potential solutions: add battery heaters to the EPS architecture; heat the batteries using heat given off by the CPUs, or do nothing. Selecting active heating will require the C&DH lead to incorporate heat sensors into their subsystem's architecture. Passive heating adds a new design task to Structures: design a conductive path from the heat source electronics to the batteries. There is a need to communicate the decision so that the other subsystem leads will know which design tasks to pursue.

The arrival of new information changes the outlook for the heating issue. In series of email exchanges with class mentors, the team learns that the relationship between timing of orbit induced thermal cycling and the batteries charge/discharge cycles should be examined more closely. It may turn out that the batteries are not charging when they in a cold phase. After more investigation into the battery specifications, the team learns that the batteries may be more susceptible to damage from high temperatures.

Design evolution of payload communications system

The KatySat Comm system sends telemetry, health and status data to the ground, and receives operations data and commands. Onboard the satellite C&DH exchanges data with the Comm system. On the ground, the communications system interfaces with high bandwidth and low bandwidth radios. Like the EPS system, the communications system is made up of multiple subsystems including antennas, high rate and low rate radios, terminal node controllers (TNC's) and other data converters.

The communication subsystem is the greatest consumer of power on the satellite, so the communication system design greatly constrains the power budget for the rest of the satellite. During initial development of the power budget meeting, EPS determined that it would be very difficult for the system to

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generate enough power given the current configuration of components. In response, the Comm lead suggested that high bandwidth radio could be cycled on and off to reduce the communication system power load. He further remarked that making this change would entail writing code to turn the radio on and off. The exchange at this meeting also shows that the engineers were aware of how their subsystem design decisions would affect the system, and what trades should be considered. In this particular case, adding complexity to the communication system design would lower its power needs. Also, the engineers shared information about the possible *range* for the amount of power the communication subsystem might need, depending on the outcome of the design. Having the radios on all the time gave an upper boundary on the power needs, and powering down the radios (or eliminating components) provides a lower bound.

One decision point we examined closely, was the selection of the communications architecture. The decision problem is to choose an architecture from among five proposed design alternatives. The alternatives are varying configurations of different radios and other communications components. Although the Communications team has identified selection criteria—more functionality and less complexity/risk—it turns out they are also constrained by the (currently unknown) availability of hardware and software components. That is, they would like to select the alternative with the highest functionality and the simplest implementation, but if they are able to obtain certain components sooner, then they will be biased toward the architectures using that component. They feel pressure to select an architecture early in order to help bring the system design to convergence. On the other hand, by selecting an architecture early on, they run the risk of not being able to use the best components.

When one of the desirable hardware components became available, the team eliminated the architectures that did not use that particular component. When they reconsidered the remaining alternatives, they decided that they didn't need to finalize their selection yet and that it was to their advantage to put off the decision. In this case, new information, the availability of the hardware simplified the architecture decision problem by eliminating choices.

3.4 Findings

Decision points

We catalogued about a dozen instances in which the team needed to decide among several options for both architectures or components. These decisions occurred at all levels of the system hierarchy. At the system level, one of the major trades studies was selecting an architecture for the spacecraft bus. A low level decision was picking a battery technology.

One of the decision support techniques the team used was to make tables of the characteristics and advantages of each option. Some tables were Pugh Matrix type tables, whereas others had ad hoc organization. In the simplest cases, such as battery selection, the tables compared the technical specifications from different models, so inspection could be used to make the selection. In complex trades, we found that the team did not layout their trades systematically, especially when it was difficult to find independent selection criteria. In other cases, making systematic comparisons did not make sense because new information changed the decision space. In the case of the communications architecture, the selection criteria the team originally proposed turned out not to be deciding criteria. This suggests that the engineers are not always consciously aware of the criteria that are important to them, and that the importance of the criteria changes during the design.

Information flow/Design state awareness

When the program manager asks the engineers about the flash memory they would require if there is a camera in the payload. In this discussion, the engineers have just communicated the uncertainty in the payload power requirements by saying they may or may not have a camera on board, and by bringing up the options for external memory for the camera

To shrink the knowledge uncertainty levels (and provide a better basis for obtaining power estimates) the professor suggests that the students continue to look at past cubesat designs, paying attention to the components they used. This is an example of reducing knowledge uncertainty by doing more research. Eventually, as the design progresses, each of the subsystems will have a better idea of their power needs, and the power system will be refined based on updated power requirement parameter values.

In KatySat, the entire team maintained awareness of the state of the system because there was ample time during class meetings for both formal and informal exchanges. At formal meetings, the subsystem leads presented design problems, analysis results or trade studies to the entire team. The design problem were worked out on a white board or on a wall sized video display hooked up to laptop computers. These meetings often produced design documents that could be disseminated to all team members. During informal exchanges, the students communicated useful knowledge even if the meetings were not initiated to solicit specific information. At one exchange, the Communications lead asked the engineer who was analyzing satellite trajectory how a passive attitude determination system would work on KatySat. The two team members worked at a whiteboard to diagram the spacecraft attitude at different points in its orbit. Although the Comm lead had asked for information on how the ADS worked, working out the orbit attitude changes transmitted information on the likely ground station coverage for the satellite.

Sources of uncertainty

Specific sources of uncertainty included open design alternatives which ranged from selecting specific models for a component to selecting an architecture for a subsystem. Open design alternatives also rippled into uncertain design constraints for interactive subsystems. Another source was uncertain performance due to potential failures.

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Design tasks and uncertainty management

We categorized the uncertainty reducing design tasks. These included researching past designs, researching external information sources such as outside experts or component technical specifications, and performing engineering analyses to predict performance characteristics. In the case of uncertainty due to failures, the design tasks included analyzing failure criticality and functional performance in both nominal and off-nominal operations.

Other design tasks increased uncertainty, or at least awareness of uncertainty. In the discussion described above where the communications lead and the trajectory analysis engineer worked out the satellite attitude changes, they noted that at one point in the orbit, the satellite could flip and get stuck in the wrong orientation. (This was a possibility since they were using passive attitude determination.) The battery thermal environment issue also resulted in tasks which increased awareness of uncertainty. As new information came in, understanding the thermal environment resulted in increased uncertainty of the functional performance of the batteries..

4 TEAM X STUDY

In this section we present a case study of a conceptual mission design team at JPL's Project Design Center. This design team is also known as Team X. The goal of our study was to understand how the design space was explored during a mission design project and how the team managed uncertainty. In particular, we wanted to understand how and when information flowed among the team members during the course of a design.

4.1 Background

Team X is a concurrent engineering team that has the capability to design a an entire mission in one week. Their product is a conceptual design that includes the mission architecture, equipment lists, launch vehicle and estimates for cost and schedule. The team was formed in order to shorten the time required to develop a space mission proposal, a process that previously required months of work.

The team size is very small, about 12 to 20 members, depending on the mission concept they are working on. Most of the team members are design engineers, and each of these designers works on a single subsystem. One of the engineers attends system integration tasks including requirements flow down. In addition, one of the engineers acts as a team lead directs the overall design process.

The time constraints combined with the tight coupling of subsystems result in high collaboration and communication demands. These demands are met through a combination of a streamlined organizational structure, highly optimized design process, and a team specific physical environment with networked computers. The fast-paced, interactive environment also requires a particular work style. Team members and managers often attribute the success of the Team X concept to the expertise and personality of the team members themselves.

While working on a design, the team will meet in a common space for three design sessions lasting three hours each. Use of a common space is a key factor in their rapid design process because it enables real time communication among team members [13]. Engineers can quickly iterate subsystem designs since they can easily communicate their architecture and parameter changes face-to-face. Further, this co-location allows the engineers to passively receive information since they can overhear conversations. Part of the team lead's responsibility is to maintain an awareness of each subsystem's design state so as to facilitate communication among designers who have tightly coupled interfaces and design parameters.

A distributed database application provides automated parameter sharing [14]. In their concurrent engineering process, all cross-subsystem design parameters are enumerated and assigned to a subsystem engineer. The parameter "owner" has primary control over that parameter's value. In addition, the team's system engineer uses the application to flow down parameter constraints to integrate system wide parameters such as cost, mass and power.

4.2 Field study methodology

We observed the team over the course of a week as they worked on a robotic lunar lander mission design. The mission concept was initiated by an internal NASA customer. Prior to the field study we had participated in requirements definition for the mission, so we were familiar with the mission's concept of operations and many of its technologies. During these observations, we took detailed notes coded for time and speaker. We also conducted short qualitative interviews during the design sessions to follow up and obtain details on specific design issues and utterances that we recorded. Other data sources included the final report and intermediate design documents and notes produced by Team X members.We later analyzed our data to determine decision points and the parties involved in making decisions. For each decision point we noted the related decision elements. (The decision elements are the same a those summarized in Table 1).

4.3 Observations

At the beginning of first design session the team lead delivers a 10 minute introduction to the mission concept and a starting point for the mission design. Within these first few minutes the, two of the designers begin discussing a particular component to consider for the baseline design. Next, the NASA customer briefed the team on their goals for the design mission concept, key technologies that they expected to be used during the mission, driving requirements, and the parts of the mission system where they wanted to see the most design fidelity. Team X had received much of this information prior to the first meeting, but this was the first time they were able to directly question the customer.

In their questions, they sought more detail on requirements and on how the customer had derived their information. For instance, the customer estimated that one of their onboard

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software technologies would require a certain amount of CPU power. The software subsystem engineer asked where this estimate had come from. The customer responded that the numbers came from an earth orbiting satellite which carried the software.

The team lead then elaborated on the mission design starting point and how he wanted the design space to be explored. For the starting point, the team lead specified a particular launch vehicle, flight trajectory and propulsion capability. He also suggested that the selection of the launch vehicle would drive the rest of the design.

During most of each design session, team lead remained actively involved in directing the design space exploration, initiating design tasks. The design tasks were directed at small subteams that the team lead expected to work together for that task. For instance, he asked the ground systems designer to work with the trajectory designer to estimate a telemetry data volume.

Throughout the project, the launch vehicle selection continued to be a major design driver. Over several iterations, a launch vehicle would be selected, and the team would work on making their subsystems fit within the launch capabilities, in particular the launch mass. Each time the design failed to converge, a different, and usually larger, launch vehicle would be proposed and the cycle would repeat.

Between two of the sessions they realized that their parametric models were not well suited to the mission concept they were designing. The models produced mass and cost numbers that were discovered to be invalid because the models' assumptions were violated. This problem arose because the customer's mission concept and requirements had with aggressive cost, schedule and mass constraints that differed significantly from typical mission concepts and violated the models' assumptions. The design team had to put resources into modifying their models to make them more closely

4.4 Findings

Decision points

Establishing a consensus on the driving requirements at beginning of the project was an important part of defining a common context for evaluating decision.

Addressing particular design issues and decisions is a particular design task. The team lead often directed these tasks, laying out the order in which major issues were addressed and decision alternatives investigated. Ideas for design alternatives came from the customer as well as from the team members. The selection criteria were drawn from the design requirements, but it appeared that most criteria were generic to space mission design. In trade studies where different alternatives were evaluated using the same criteria, the team tended to give priority to known technologies with low development risk. They did not evaluate all alternatives to the same extent and put more effort into investigating design alternatives that used the technologies they felt more comfortable with.

Information flow/Design state awareness

As described in the background section, the ability for the engineers to communicate in real-time because of their co-location was a key factor in maintaining design awareness. This situation awareness guided the subsystem design tasks of each of the designers since they knew which tasks to pursue or abandon depending on the decisions made by others. Even so, the designers needed to start tasks before they had enough information to know where to put their efforts. The team lead and the system engineer were instrumental in keeping the team in sync. The systems engineer monitored the parameter values in the parameter sharing software and walked around the room to query individual team members.

Sources of uncertainty

We observed new sources of uncertainty in addition to those we observed in the KatySat study. Low TRL level was a significant source of uncertainty and design risk for this mission concept since the customer asked Team X to consider newer less proven technologies. Another source we hadn't seen before was the use of mismatched of parametric models. Lack of knowledge of model assumption violation resulted in abandonment of feasible design alternatives.

Design tasks and uncertainty management

A design task for investigating design alternatives was refining design model to obtain more accurate parameter values. These models were refined until the designer had enough confidence (that is, uncertainty reduction) in the numbers produced by it. The uncertainty in their numbers was managed by adding contingency. The design space could be expanded by reducing contingency and thereby increasing uncertainty and design risk.

5 UNCERTAINTY MODELING

Based on our analysis of the case studies presented above, we developed a methodology for modeling design team decision-making, uncertainty reduction and information flow. The model is represented as a flow diagram where different types of nodes and edges to represent the decision elements that were described in Section 3.2. The intent of the model is to make the evolving state of a design explicit with respect to major decision points and information flow. This section explicates the diagram representation using a model of the Team X case study as an example. We then show how the model can be used to analyze the design process.

5.1 Flow diagram representation

In describing the flow diagram modeling methodology, we will refer to the Team X diagram in Figure 2 which models a part of the Team X design process described in Section 4. The diagram is essentially a directed graph with a few other symbols beyond nodes and edged. Read from left to right, the diagram shows how the design state varies over time. Note how the directed edges always move from left to right, that is, always move

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forward in time. In the following paragraphs we describe the meaning of the various symbols.

Requirements nodes

The black rectangles with thick lines and sharp corners are *requirements nodes* and are used to represent design requirements. In Figure 2 two requirements nodes are located on the left side of the diagram. They depict the requirements *low mass*, and *low cost.* We include a representation for requirements since all design decisions at any level of detail must take the higher level requirements into account. In addition, the requirements provide context for understanding decision outcomes.

Decision nodes

The blue boxes with rounded corners are *decision nodes*. They can be used to represent points during the design process where a design issue arose and lead the need to select from among design alternatives. If an edge goes from one decision node to another decision node, the later node can be interpreted as a subdecision needs to be resolved in order to resolve the higher level decision. Edges from a decision node to a *design node* (described below) indicate that the decision point involves a selecting a design alternative.

Selection criteria nodes

The a vertical black line and bracket below decision nodes is the *selection criteria* node. The vertical list of words are the criteria that are used to select among the design alternatives that are associated with the decision. In the example diagram, the far left decision node "Select launch vehicle" is linked to the a selection criteria node labeled with three criteria: low cost, lift capability and maturity.

Design alternative nodes

Red ovals—both solid line and dashed line ovals—are *design alternative* nodes. These represent a design alternative that was considered. The alternatives with solid lines indicate that these designs choices were actively investigated, that is, resources—in this case, the engineer's time—were put into investigating or refining the design. Alternatives in dotted lines are alternatives that were considered but not yet actively investigated. Edges from one design alternative node to another indicate a transition from active work on one alternative to another. Moving from left to right, the example flow diagram shows the order in which tasks and design alternatives were actively pursued as the design progressed.

Abandoned design alternative symbol

Design alternative nodes with an "X" through them indicate that a design alternative was abandoned.

Confidence levels

The red squares below the ovals indicate the amount of *confidence* the team has in each design alternative. Confidence is measured on a scale from 1 to 5 where 1 indicates the lowest level and 5 the highest level of confidence.

Information source nodes

The small solid green oblongs are *information source* nodes. These represent information sources that provide information related to a decision. The two information source nodes "ACS" and "Struct" indicated that the ACS engineer and the structures engineer both supplied information that pertained to the selection criteria "pointing available" and "low mass" respectively.

Design epoch segments

Grey horizontal line segments represent *design epochs*. Recall

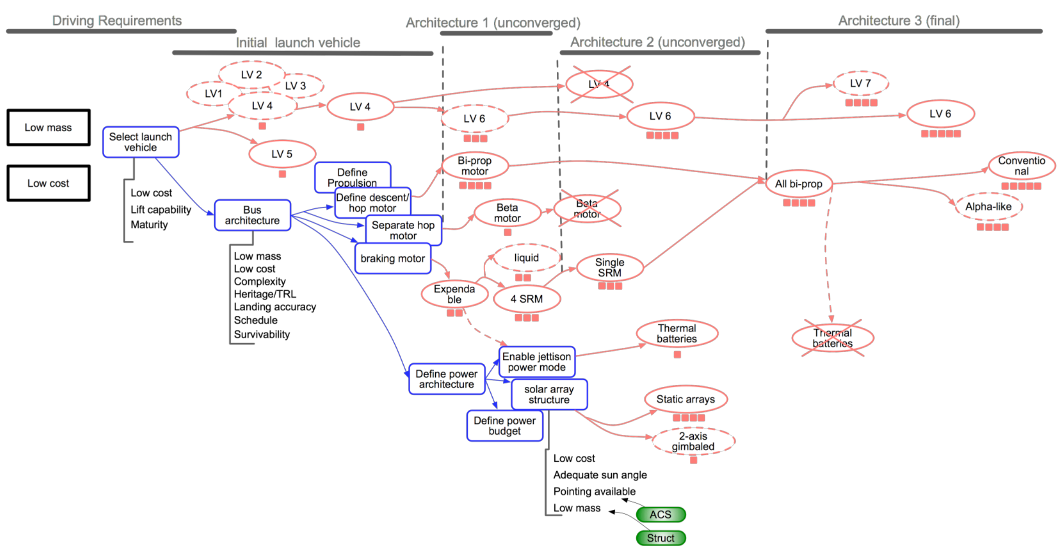

Figure 2. Example flow diagram of excerpt from Team X design process.

that time moves forward as the diagram is read from left to

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right. Each design epoch segment indicates a major phase of the design and qualitatively indicates that a portion of time was spent on particular design tasks. The absolute lengths of the segments do not correspond to actual hours spent in each epoch. In the example diagram, the far left segment labeled “driving requirements” delineates a time period when the team was discussing and refining the design requirements.

Solid versus dashed edge symbols

Solid edges indicate a temporal relation, among other things. A dashed line indicates a causal relation. In the example flow diagram, the dashed edge from the design alternative node “all bi-prop” to the abandoned alternative node “thermal batteries” means that selecting “all bi-prop” caused abandonment of the thermal batteries alternative.

5.2 Team X modeling analysis

In this section we provide an example of how the model can be used to analyze the evolution of a design and characteristics of a design team’s process. This analysis is based on the diagram in Figure 2. The diagram models a very small portion of the mission design, focusing mainly on the progression of the launch vehicle selection and the propulsion subsystem. The state of these two design tasks are shown together because the decisions are tightly coupled, and iterating through these two tasks in tandem is a typical mission design process. One of the methodologies used by Team X is to select a launch vehicle and then size the propulsion system to launch vehicle upmass capabilities. These tasks occupy the top two thirds of the diagram. The initiation of these tasks proceeds from the decision nodes “Select launch vehicle” and “Define Propulsion. ” The initial part of the power subsystem design state is depicted in the bottom third of the diagram, proceeding from the decision node “Define power architecture.”

Design iteration

Although it is laid out linearly, the diagram still reflects the iterative nature of the design process. Each of the design alternative nodes can be interpreted as revisiting an earlier design task or decision. Consider the paths that initiate at the “Select launch vehicle” decision node. Traveling along this path from left to right traces the progression of this selection decision from early discussion of 5 different alternatives through eventual consideration of 7 different alternatives is all. Since the solid line design alternative nodes (red solid line ovals) indicate that the designers were actively investigating a particular design alternative, we can infer that each of these nodes is an iteration through the launch vehicle selection task.

Subsystem interaction

The diagram can be analyzed for subsystem interaction in a number of ways. When looking at the nodes that overlap with a particular design epoch, we can loosely infer that the design alternatives considered within any one epoch are coupled in some manner. The dashed edges make some of these interactions explicit.

During the Architecture 1 epoch, there is a dashed edge leading from the “Expendable” node to the “Enable jettison power mode” node. The expendable [braking motor] design alternative was being worked on by the propulsion subsystem designer. (Actually, it is worked on simultaneously by the propulsion subsystem designer and the attitude control system designer, but this interaction is not modeled here.) The causal relation edge indicates that this alternative will necessitate a particular power mode. We can infer a subsystem interaction because the “enable jettison power mode” decision was addressed by the power subsystem designer.

Another explicit interaction occurs in the “Architecture 3” design epoch. See the dashed edge from the “All bi-prop” node to the “Thermal Batteries” *abandoned* design alternative node. The selection of an all bi-propellant propulsion system eliminated the need for a power architecture that includes thermal batteries.

The edges from information sources nodes to other nodes also indicate a kind of interaction. This interaction is described in the next paragraph.

Information flow

The “ACS” and “Struct” information source nodes show information flow from the information source to the designers working on the “solar array structure” decision. The edges from these nodes to particular selection criteria indicates that the information was used to gain knowledge—reduce uncertainty—in the information required to make this decision. In this case, the ACS (attitude control system) designer needs to inform the power subsystem designer what the spacecraft pointing capability is. With respect to subsystem interactions, we can also infer that the ACS designer’s decisions will affect the design alternatives open to the power subsystem designer.

Uncertainty

In our modeling methodology, we make confidence in each of the design alternatives explicit. Here, increasing confidence can be seen as reduced uncertainty. By looking at the design evolution, we can see how level of uncertainty affects the search through the design space. In general, the level of uncertainty tends to drop as the design progresses. This is due to the greater level of knowledge that the designers have as they refine their models, iterate designs research new options. This is the pattern we see in the Team X diagram, and it suggests that the team takes a conservative approach to considering alternatives. Note how the “Beta motor” design alternative has very low confidence and was abandoned in the “Architecture 2” epoch. In contrast, the bi-prop motor had high confidence from the beginning and was eventually selected for the final architecture. Though this a valid strategy, it may also suggest that the team is too shy of putting effort into investigating technologies where the uncertainty is high. It may be that with only a little more effort, the confidence in this alternative would have been greatly increased.

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6 CONCLUSIONS

6.1 Implications for designing collaborative tools

Our diagram makes explicit the state of decision making and uncertainty levels during the course of a design. Unlike design rationale systems, we would like to understand which information will give a design team an awareness of the state of the design.

The evolution of most mission design systems looks very similar since many of the design tasks are generic. Generic tasks include selecting a launch vehicle, analyzing communication coverage and analyzing thermal gradients in the spacecraft bus. These generic elements can be exploited in a collaborative software system by using them to organize user interface controls.

Many of the decision criteria are also generic. For instance, minimizing mass is always a primary goal in mission design. What differs are the importance of the criteria. Many design tasks are directed towards obtaining information that can be used to evaluate decision criteria. Showing confidence levels may help the team select among design tasks, such as whether to obtain more information to reduce uncertainty and in this way optimize their efforts.

Our model shows how information flow among team members is used to communicate knowledge that help with evaluating decision criteria. Finding communication patterns with respect to design tasks and selection criteria can be used to design information pathways in a collaborative system.

6.2 Limitations and Future work

In the modeling we have done thus far, we only looked at decision problems where the design team was performing design trade studies and we treat making decision-making as the primary design task. This is a simplification of the decision-making space in the design process and a limitation of our model. We do not model decision points where the decision is to select among design tasks. At any point, the team may face the choice of continuing to investigate a particular alternative, investigating a different alternative or generating new alternatives. we should also look at this case.

Our model only represents the level of uncertainty with respect to the designer's subjective judgment of the confidence they have in a particular design alternative. However, in our field studies we have found that uncertainty arises from other sources such as potential failures or poor design models. If we are to analyze uncertainty reducing tasks, we may need to develop explicit representations for different kinds of uncertainty. We would also like to develop a metric and representation of the overall uncertainty level in the design. In this way we may be able to find patterns in the way that positive and negative uncertainty affect design outcomes.

It may be useful to explicitly model breakdowns in information flow. That is, we could model where knowledge should have been transferred between team members but wasn't. Our analysis of information flow is incomplete if we have only modeled how information actually flowed since we cannot then infer if other information could have improved the design progression.

In future work we would like to apply our methodology towards understanding how decision quality under uncertainty affects design quality. This will give us a basis of for designing better engineering design methods and tools.

6.3 Summary

We have developed a methodology to model design decision-making and information flow over time with the objective of using the model to understand how information is used and communicated within design teams. The methodology was developed based on findings from two field studies of space mission design teams. Our findings were used to define and classify decision points, paths of information flow and methods of maintaining design state awareness, sources of uncertainty and uncertainty reducing design tasks.

We presented the modeling methodology and an example of the flow diagram representation of the model. We then showed how the model could be used to analyze the progression of a design and characteristics of the design process itself. Our ultimate goals is to use this modeling methodology for designing collaborative design software.

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