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A Phenomenographic Study of How Aerospace Engineers Experience Uncertainty When Making Design Decisions

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A PHENOMENOGRAPHIC STUDY OF HOW AEROSPACE ENGINEERS EXPERIENCE UNCERTAINTY WHEN MAKING DESIGN DECISIONS

A Dissertation

Submitted to the Faculty

of

Purdue University

by

Antonette T. Cummings

In Partial Fulfillment of the

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of

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West Lafayette, Indiana

Dedicated to:

My late father: Maj. Anthony T. Cummings, US Army Ret.

and

My dear mother: Luu N. Cummings

and

To the men and women of the US Armed Forces and their families.

This work, among many others, supports design efforts to make products and services so that our country's finest defenders can accomplish their missions and come home safely.

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ABSTRACT

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This study investigated the qualitatively different ways in which engineers working in aerospace-related industries experience uncertainty as they make design decisions. This study provides insight on how engineers increase their ability to manage various forms of uncertainty as they design Large Scale Complex Engineered Systems. The results of this study are valuable for understanding learning trajectories of engineers beyond their academic experiences and for linking the professional and technical skills in industry to the undergraduate engineering learning experience.

Phenomenography, a qualitative research methodology, was employed to solicit varied experiences. Previously published literature on design, expertise, teaming, uncertainty, and decision-making informed the semi-structured interview. The twenty-five participants were interviewed; their professional experience ranged from senior design students to individual contributors in private industry to director levels of responsibility, across corporations of sub-suppliers, suppliers, and end users. The literature also provided ways to describe and validate the results of the analysis.
The analysis produced five categories of experience of uncertainty in design decisions which follow the trend of previously identified design expertise levels. There is a

dimension of quantity and quality of uncertainty that implies degree of design complexity, another dimension of skill in team engagement, and a third dimension, by which the categories are named, of an individual's personal response to encountering uncertainty. The categories follow the metaphor of a material's increasing response to stress: Brittle, Plastic, Tolerant, Robust, and Resilient. These categories provide complementary insight into the necessity of building large and trusted teams of people as part of an engineer's strategy for designing complex systems with varied forms of uncertainty.

The critical elements that participants identified in their design experiences allows engineering educators to develop learning interventions to simultaneously enhance a student's understanding of designing complex systems and of strategically engaging in teamwork. This study also supplies engineering educators with more detailed insight into student's possible emotional responses to uncertainty as they engage in designing complex systems. Overall, the impact of this study is to equip educators and students to take on the grand challenges of engineering design in more comprehensive ways.

CHAPTER 1. INTRODUCTION

1.1 Design in Aerospace Engineering Contexts

Engineering, while still including the engineering sciences, is increasingly returning to design as the "art of engineering" (Seely, 1999). Design, an ABET outcome (ABET, 2015), is considered an activity central to engineering (Dym, Agogino, Eris, Frey, & Leifer, 2005; Simon, 1996). Researchers have shown that key features of design problems are being ill-structured (Goel & Pirolli, 1992; D. H. Jonassen, 2000) and co-evolving with the solution (Dorst & Cross, 2001). Engineers, therefore, need to be aware of uncertainty and be capable of engaging in design amongst these realities.

Because of the scale and complexity of the projects, designing systems in aerospace must be a team effort (Roth, 2007). Therefore, engineers in aerospace need to have their "professional skills" developed, especially teamwork and communication that are included in the ABET criteria (Shuman, Besterfield-Sacre, & McGourty, 2005). Researchers have clearly identified design as a social process (Louis L Bucciarelli, 2003), which means that the context of the design matters, including the intentions of the designers and the culture of the users, and the boundaries between them being negotiable. It also means that design is done in teams and often diverse and multidisciplinary teams. Investigations into multidisciplinary teamwork in authentic design tasks may guide our understanding of the social aspects of design (Adams, 2003; Austin-Breneman, (Adams, 2003; Austin-Breneman, Honda, & Yang, 2012; Dym et al., 2005; K. Sheppard, Dominick, & Aronson, 2004; Thom & Gerbracht, 2008). Especially, expert teams, but not engineering teams, have been studied and their practices may guide our understanding of professional teamwork (Ericsson, 2006) in Naturalistic Decision-Making Environments (Ross, Shafer, & Klein, 2006).

Unfortunately, the aerospace engineering industry is difficult to study *in situ* because of the projects' large scales and complexities (Deshmukh & Collopy, 2010). The aerospace engineering industry is constrained by the performance measures of safety, technical, cost, and schedule (National Aeronautics and Space Administration, 2011). These constraints are interdependent. At a deeper level, quality and performance can be constrained by myriad technical parameters that may also be interdependent and contrary to each other. Aerospace engineering design is fraught with technological limitations that can be measured as cost and schedule limitations.

The aerospace industry is risk-averse and seeks to reduce risk and cost by reducing uncertainty (Hamraz, Caldwell, & Clarkson, 2012). The term *aerospace* will be used here to include aviation and space applications. Lately, the aerospace business has taken a systems-of-systems approach to design (Bloebaum & Rivas McGowan, 2012; DeLaurentis & Crossley, 2005; DeLaurentis, Crossley, & Mane, 2011; Lewis & Collopy, 2012) in order to decompose the design space and to integrate the solutions with awareness of and planning for uncertainty resolution. Uncertainty plays a significant role in design, especially in the aerospace industry.

1.2 Experiencing Uncertainty in Design

Successfully managing uncertainty is a desirable professional skill, and it may have several names. There is a distinct call in industry and academia alike for engineers to be *tolerant of ambiguity* (Altman, 2012; Atman, Turns, & Sheppard, 2011; Crismond & Adams, 2012; Goff & Terpenny, 2012; Koretsky, Kelly, & Gummer, 2011), to be *flexible* (Committee on Developments in the Science of Learning, 2000; Daly, Adams, & Bodner, 2012; Gorman et al., 2001; Walther, Kellam, Sochacka, & Radcliffe, 2011), and to be *adaptable* (Atman, Kilgore, & McKenna, 2008; Committee on Developments in the Science of Learning, 2000; Gorman et al., 2001; McKenna, 2007; Rayne et al., 2006; Schwartz, Bransford, & Sears, 2005). These concepts appear to be in contrast to the Piagetian human tendency to attempt to reduce uncertainty and non-equilibrium (Wankat & Oreovicz, 1993). How do people, especially designers, move from wanting to reduce uncertainty to being tolerant of uncertainty?

As the aerospace industry engages in designing Large Scale Complex Engineered Systems, uncertainty must be confronted by the designers. In particular, Deshmukh and Collopy (2010) posed fundamental research questions that this work explores: "*Investigation Area 2) Uncertainty and Decision-Making c)* Where is the optimal balance between gathering information to refine uncertainties and making a design decision with already available information? ... *Investigation Area 6) Research in Engineering Education a)* What are the key attributes of a successful engineer in the design of large complex systems? How can an aspiring engineer acquire these attributes? and *b)* For developing engineers, how effective is learning from failure? What is gained in learning from success?"

A path of exploration for these research questions is to investigate aerospace engineers' design and learning experiences. Previous work has investigated which ABET outcomes are most important in the professional workforce, where teamwork, data analysis, and problem solving were top results (Passow, 2012). Passow's work asked the questions using ABET outcome vocabulary, but did not ask about uncertainty. This rigorous research study can shed light into both experiences and cognition of uncertainty in particular, especially in the professional workforce. Understanding the relationship between experiences and cognition can have an impact on the undergraduate curriculum to help students develop these skills more efficiently through the development of appropriate learning interventions.

1.2.1 Literature Overview

The literature review explores key topics: the context of aerospace engineering design; the concept of uncertainty from multiple perspectives; and the development of expertise in design. Here is a brief description of these three topics, and from these topics, research questions were developed to explore the gaps in the current literature.

There is a small but growing body of literature stemming from recent conferences and workshops on Large Scale Complex Engineered Systems in aerospace engineering design (Bloebaum & Rivas McGowan, 2012; Lewis & Collopy, 2012; Rivas McGowan, Seifert, & Papalambros, 2012). In particular, the authors note a propensity for the aerospace industry to reduce risk through reducing uncertainty. However, more knowledge may cost an unallowable amount of money and schedule to obtain. Is it worth the cost and schedule to pursue the knowledge? How do design engineers make decisions in this environment? How do design engineers cope with uncertainty?

A definition of uncertainty is necessary because there are many perspectives, from engineering (Van Bossuyt, Dong, Tumer, & Carvalho, 2013) to business (Herman, Stevens, Bird, Mendenhall, & Oddou, 2010) to psychology (MacDonald, 1970; McLain, 1993) to communications (Bradac, 2001). Because of the specific context of aerospace engineering, a taxonomy of uncertainty in Large Scale Complex Engineered Systems (LCSES) will be employed here to define and classify forms of uncertainty in design (Thunnissen, 2003). Mainly, there are four types of uncertainty in LCSES: ambiguity, epistemic, aleatory, and interaction, which will be further explored in Section 1.4 and Section 2.5. Because of an engineer's likelihood of becoming specialized in a subject relevant to aerospace businesses, an engineer may develop different levels of awareness and responsibility for different forms or sources of uncertainty as they progress through their careers, assume different roles, acquire experience and develop expertise..

The development of expertise and the difference between novices and experts have been studied in various disciplines and contexts, including physics problem solving, chess, and design (M. Chi, Glaser, & Rees, 1982; M. T. H. Chi, Feltovich, & Glaser, 1981; Ericsson, 2006). The *Engineering Education Research Handbook* (Johri & Olds, 2014) qualitatively describes students (presumably novices) as having a fear of uncertainty and expert designers as having the willingness to manage uncertainty, which seem to be start and end points but it does not provide a path for moving from start to end. Additionally, Skill Theory (Fischer, 1980) suggests a gradual development of skill through tasks that require the intercoordination of lower level skills. But there does not appear to be an investigation into the experiences and tasks that induced expert designers to develop the skill to manage uncertainty.

1.2.2 Research Questions

Within the context of design of Large Scale Complex Engineered Systems in aerospace engineering, there are a multitude of forms of uncertainty that designers may or may not encounter. Designers may have developed strategies for managing different types of uncertainty, especially as designers have moved from academia to the workforce. The primary research questions for this study are:

1. What are the qualitatively different ways that engineers in aerospace businesses experience uncertainty in design decisions?
2. How do aerospace design engineers develop successful uncertainty management skills?

1.3 Purpose of Study

The purpose of this study is to investigate the lived experiences of aerospace engineers who practice design in order to understand how they experience, address, and manage different types of uncertainty. While there are varied ways designers address and manage uncertainty, it is reasonable to expect that there are a finite number of ways in which uncertainty in design decisions is experienced. Identifying and categorizing these ways is a first step in understanding the progression from novice to expert and the second step is to develop approaches to promote an engineer's development toward expertise.

This study gives voice to working professionals across a spectrum of years of experience in design, corporations, and responsibility for decision-making.

Within the aerospace industry, there are decision-makers who have made judgment calls and have seen the consequences of those decisions, even though the situations were full of uncertainty from multiple sources. It is imperative to include engineers who have decision-making authority in design and who have been identified by peers as good designers. Peer identification of being a good designer, including being promoted to decision-making roles, implies that those decisions had desirable consequences and that the designer's behaviors include some measure of successful management of uncertainty. For maximum variation of understanding skill development, lesser-experienced engineers were also included.

This research employed developmental phenomenography (Bowden & Green, 2005), a qualitative approach, to understand the variation of how professionals experience uncertainty in their careers as decision-makers. Participants were identified through chain sampling. Data was collected in semi-structured interviews, and a whole transcript was the unit of analysis. Categories of the transcripts compose the outcome space of results. The attributes of the outcome space are parsimony, logical relationships, and simplicity.

While the outcomes may not represent a universal truth, the outcomes are educationally useful. The three corners of the triangle, research, practice, and instruction, employed with express intent of having each one inform the others, provide a firm foundation and a practical use for the results of this study. This research will link professional practice to instruction.

1.4 Overview of Experiencing Uncertainty

The key concept in this study is uncertainty, further defined in Section 2.1. Uncertainty can be classified in complex systems as *ambiguity* (imprecise vocabulary terms and expressions), *interaction* (unanticipated interaction of many events and/or disciplines), *aleatory* (cannot be reduced with more knowledge; frequently represented as a probability distribution), and *epistemic* (can be reduced with more knowledge) (Thunnissen, 2003). The experience of uncertainty will be framed in the context of making design decisions in aerospace applications. Because there are many identified forms of uncertainty and possibly coupled management strategies, it is prudent to include engineers who have experienced multiple types of uncertainty in multiple projects.

Criteria for maximum variation in sampling of the population include the participants' professional responsibilities within the larger scheme of their employers' relationships to one another. First, the participants have various education backgrounds, various career trajectories, and various work responsibilities. The participants' gender, race, and national origin may also affect their awareness of uncertainty. To the extent that participants report the effects of these variables, their experience will be included.

Second, the context of aerospace design, namely, system-of-systems, introduces a criterion for variation. Systems-of-systems considers the companies working aerospace projects as having various levels within systems-of-systems, such as a raw material supplier, a subsystem supplier, an airframe integrator, or a primary operator, labeled "Base, C, B, A, and OES" (Talley & Mavris, 2008). The level at which a company operates implies different priorities in costs, qualities, and schedules, which in turn may become an uncertainty for others at different levels. These criteria from Talley and Mavris will be identified in the data collection efforts.

1.5 Educational Implications

The foremost contribution of this study is the clear description of actual practices and behaviors in managing uncertainty in the context of the aerospace engineering design industry. Up to now, literature proposes ideal design process models with intent to generalize (Dubberly, 2005; Ullman, 2003), or investigates actual practices and behaviors of designers outside of aerospace engineering because of limited access for researchers. The aerospace industry has distinguishing characteristics and its own culture that make applying generalized models problematic. Aerospace merits its own investigation to better inform the field and the pathways for students pursuing studies toward this field. This description will provide aerospace engineering instructors a vocabulary to describe to students the industry that eagerly awaits them.

A second contribution of this study is the investigation of content and tasks that may move students from a fear of uncertainty to some greater level of confidence to persevere in design in the face of uncertainty. From this foundation, content and tasks can be aligned in order to create interventions and learning modules for the undergraduate curriculum, whether it is in a design course or in an engineering science course or some combination and sequence of both. This investigation will tell where certain tasks and experiences belong.

A third contribution of this study is the future operationalization of management of uncertainty in order to be measured quantitatively. This study may reveal indicators for which a scale can be developed specifically for management of uncertainty within an engineering design context. This will be qualitatively different from the scales developed in other disciplines such as psychology and business management (MacDonald 1970, McLain 1993, Herman et al. 2010). This leads to future research questions:

1. How can an aerospace engineering student's management of uncertainty in design decisions be measured?
2. What are effective interventions and classroom modules that increase an aerospace engineering student's ability to manage uncertainty in making design decisions?

Primarily, this work focuses on the professional formation of undergraduates, a topic of national interest (Douglas, 2015). The undergraduate curriculum benefits by staying up to date with industry practices. Undergraduates have the opportunity to be more prepared for the competitive high-stakes workforce. They have the opportunity to practice difficult aspects of design. They have an opportunity to understand the workforce they are about to enter. Industry gains new employees who are potentially more flexible, more adaptable, who manage uncertainty well, who tolerate ambiguity well, and who make evidence-based design decisions.

CHAPTER 2. LITERATURE REVIEW

The *Cambridge Handbook of Engineering Education Research* (Johri & Olds, 2014) and the *Cambridge Handbook of Expertise and Expert Performance* (Ericsson, 2006) summarize the state of research in those areas and provide key researchers to review. This framing bounds the investigation of expert decision-making behaviors of individuals and organizations in real-life situations full of uncertainty. Firstly, the handbooks describe at a high level how experts behave and think individually inside and outside of an engineering design context. Secondly, the expertise handbook describes qualitatively the characteristics of expert teams in Emergency Management roles, usually in High Reliability Organizations (HROs) such as medical emergency rooms and aircraft carriers (Weick & Sutcliffe, 2007). Lastly, these handbooks note a significant need for:

1. An investigation into the context of Naturalistic Decision Making (NDM) in which uncertainty plays a major role (Ross et al., 2006)
2. A comparison of workplace practices to undergraduate work practices.

Table 1.5.1 below shows the themes that I explored in pursuit of understanding the scope of relevant published research. For clarity, these themes are divided into categories of context, social process, decisions, skills, and learning. The following sections of this chapter provide details of the most relevant results of this literature review (highlighted in bold italics in Table 1.5.1), identifying relevant results to date, key areas for future research and unanswered questions. The unanswered questions identified become the research questions that guide this study.

Table 1.5.1 Classification of themes and key concepts for this study.

Context	*Social Process*	*Decisions*	*Skills*	*Learning*
Large Scale Complex Engineering Systems	***Expert Teams***	***Naturalistic Decision Making***	***Manage Uncertainty***	***Skill Theory***
Aero	Narrative	Decision Making	Deal with uncertainty	Piagetian Constructivism
Engineering Design	Sense-making	Decision Theory	Uncertainty	Expertise
Aerospace Design	Organization Theory	Utility Theory	Ambiguity	Project-based Learning
Aeronautical Design	Myers Briggs Type Indicator	Information Value Theory	Tolerance for Ambiguity	Case-based learning
Aviation	Social Constructivism	Expected Value Theory	Flexibility	Cognitive Flexibility Theory
Mechanical Design	Social Learning Theory	Intelligent Real-Time Design	Adaptable	Aerospace Education
High Reliability Organizations	Community of Practice	Decision-based Conceptual Design	Evaluation	
Systems-of-systems	Attribution Theory	Competing Values Framework	Assess Risk	

2.1 Definitions and Sources of Uncertainty

Uncertainty has different definitions and applications to different disciplines; therefore, acknowledgment of definitions specific to aerospace engineering design is necessary for this study. Uncertainty (Thunnissen, 2003) can be classified in complex systems as *ambiguity* (imprecise vocabulary terms and expressions), *interaction* (unanticipated interaction of many events and/or disciplines), *aleatory* (cannot be reduced with more knowledge; frequently represented as a probability distribution), and *epistemic* (can be reduced with more knowledge). Epistemic uncertainty is further classified as *model* (approximation errors, programming errors, and numerical errors), *behavioral* (design, requirement, volitional, and human errors), and *phenomenological* (attempt to extend the 'state of the art'). Thunnissen's taxonomy is reproduced in Figure 2.1.1 below. These classifications provide key framing for understanding designers' experiences with uncertainty.

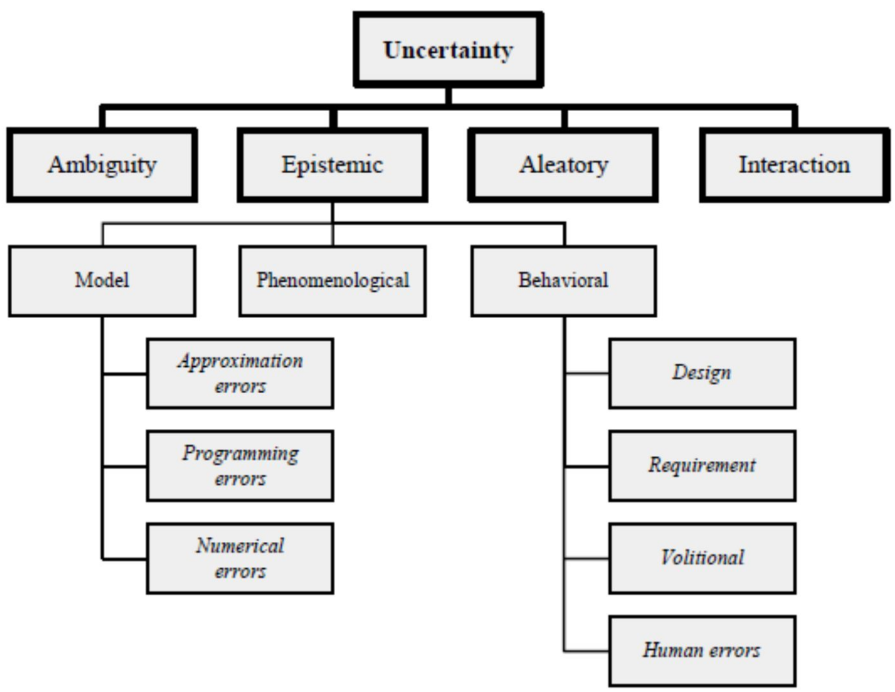

Figure 2.1.1 Reproduction of Figure 14 Uncertainty Classification for the Design and Development of Complex Systems (Thunnissen, 2003).

Some sources of uncertainty have been identified in previous research which also fit into Thunnissen's taxonomy. Uncertainty represented mathematically is common (Fellin, Lessman, Oberguggenberger, & Vieider, 2005). Design as a social process (Louis L. Bucciarelli, 1994), particularly in engaging multiple perspectives (Rayne et al., 2006), could be classified as interaction. Design and engineering thinking can be decidedly nonverbal (Hegarty, 2004) and visual representations can be ambiguous (Eppler, Mengis, & Bresciani, 2008). Verbal communication at a global level (Downey et al., 2006; K. Sheppard et al., 2004), at an ethical level (Van Bossuyt et al., 2013), and at a review and critique level (Cardella, Buzzanell, Cummings, Tolbert, & Zoltowski, 2014) can be ambiguous. Management of ethical uncertainty may include maintaining the ambiguity instead of simplifying the cases (D. H. Jonassen et al., 2009). Because of the inclusiveness of Thunnissen's taxonomy, I selected this construct for describing uncertainty in aerospace design.

2.2 Context: Design Environments

There are several ways of viewing the aerospace industry and examples that follow. While the focus is aerospace engineering, it may be reasonable to apply these concepts, skills, and behaviors to other engineering disciplines. This section highlights key views and accompanying vocabulary that will be used throughout my work.

Firstly, a Systems-of-Systems view to the aerospace industry provides context for decision-making based on different company priorities, norms, customers, and suppliers (DeLaurentis & Crossley, 2005; DeLaurentis et al., 2011; Talley & Mavris, 2008). One macroscopic view of systems-of-systems includes the attributes of "physically distributed systems, prime dependency of overall functionality on linkages between distributed systems, and system heterogeneity, especially the inclusion of sentient systems" (Delaurentis & Callaway, 2004), where a single aircraft may be seen as the α level. A second view will be used here, from Talley and Mavris (2008) to describe various companies within the hierarchy. At the top are Operational Environment and Scenario (OES) operators. The intermediate levels could be airframe integrators (A level), powerplant integrators (B level), and subsystem integrators (C level), whose customers are each other and the OES operators. The base level (D level) could be suppliers to the B and C level operators. It is reasonable to assume that aerospace engineers have an awareness of their relative location within the hierarchy of suppliers, may have been employed at several different levels over their careers, and may have reflected on encountering and managing the effects of different company cultures.

A second view of the aerospace engineering industry is the research-informed concept of Naturalistic Decision Making as a way of describing "the real world" workplace environment. Key elements of a Naturalistic Decision Making (NDM) environment include: ill-structured problems, uncertain dynamic environments, shifting and competing goals, action/feedback loops, time stress, high stakes, multiple players, and organizational goals and norms (Ericsson, 2006). The aerospace engineering design environment has all the elements of an NDM environment. Understanding the details and nuances of these activities in the workplace will be the first step to making a comparison of workplace and classroom practices. Ultimately, the aerospace engineering design business strives to resolve uncertainties in order to positively affect their cost and schedule requirements, especially to avoid failure, rework, and rebuild costs.

A prime example of research in the aerospace design environment is an investigation of cross-disciplinary teamwork in the Mars Expedition Rover during the first 90 Martian days of the mission (Paletz, Schunn, & Kim, 2013). Four researchers visited the site and captured 400 hours of video data of operations and conversations. This work uses the high-stakes dynamic environment to explore the use of analogy with multiple players from multiple disciplines. Analogy by itself is ambiguous (Ball & Christensen, 2009), thereby introducing uncertainty in communication to uncertainty of the function and performance of the Mars Rover. This work shows there is a tangential relationship of their research questions on analogy to my research questions on uncertainty, and provides insight on the large volume of data that could be collected by observation of a large scale project.

A third view of aerospace concerns Large Scale Complex Engineered Systems (LSCES) that require explicit design methodologies in order to be successful (Bloebaum & Rivas McGowan, 2012; Lewis & Collopy, 2012; Rivas McGowan et al., 2012). One assumption is that the industry can reduce risk and therefore reduce cost by reducing uncertainty (Hamraz et al., 2012). Adherence to a design process or method may identify sources of uncertainty and methods to resolution before rather than after a failure. Several design methodologies merit mention, since participants may borrow vocabulary and concepts from these methodologies as they describe their experiences.

One methodology called Robust Design attempts to account for uncertainties and communicate the associated risks to decision-making parties (Talley & Mavris, 2008). Originally Robust Design was experimental and focused on obtaining consistently manufactured parts (Park, Lee, Lee, & Hwang, 2006). The method separates controllable from uncontrollable factors that influence the outcome of the process. Uncontrollable factors are considered as noise to the process, and controllable factors are adjusted to counteract the effects of noise by designers to obtain the desired output. Robust Design has been expanded to capture the effect of multiple decision-makers negotiating trade-offs in design (Kalsi, Hacker, & Lewis, 2001). The design method was once focused on tangible parts but has now been applied to the people that participate in the design and production of those parts.

A second design methodology, Design for Six Sigma, part of Total Quality Management, is popular for aerospace businesses with high volume manufacturing (McCarty, Daniels, Bremer, & Gupta, 2005). DFSS provides a toolbox for teams of engineers to gather data and create solutions in prescribed design phases. The Six Sigma title refers to the statistical standard deviation, where the output of the process is within specifications out to the sixth standard deviation, or 3.4 defects per million opportunities. There is a clear emphasis in this design methodology to eliminate mistakes and sources of deviation, especially in high volume production. High-volume low-error production, or lean production, may be relevant to some aerospace companies, such as fastener or raw material suppliers, and may not be as relevant to airframe and powerplant integrators, depending on the mindset of their leadership team.

A third methodology, Systems Engineering Design, employs probability and statistics to represent risk (Green et al., 2006; National Aeronautics and Space Administration, 2011). In particular, NASA emphasizes continuous risk management in the hands of informed decision makers, stakeholders, and Subject Matter Experts. The use of probability and statistics implies quantifying risks to compare to performance measures. To that end, many methods and tools have been developed to model and quantify uncertainties (Nikolaidis, Mourelatos, & Pandey, 2011). The general view, then, is that emphasis has been placed further developing models for forms of uncertainty that can be quantified. I expect to see the use of *risk* as an indicator of uncertainty among my participants.

2.3 Design as a Social Process: Expert Teams

It is significant to practice teamwork at the undergraduate level because it is an engineering industry reality (D. Jonassen, Strobel, & Lee, 2006). Because aerospace design of complex systems is a team effort (Dym et al., 2005; S. Sheppard & Jenison, 1997; Thom & Gerbracht, 2008; Wellington, Thomas, Powell, & Clarke, 2002), successful team behaviors must be explored. Teams are distinct from mere groups in that teams have goal interdependence, resource interdependence, and member interdependence in order to succeed (Adams, 2003). While there is a tendency among engineering students to foster friendships and study groups (Godfrey & Parker, 2010), friendship alone does not constitute a team. Therefore, educators should provide students an opportunity to practice interdisciplinary and multidisciplinary teamwork in authentic design tasks (Austin-Breneman et al., 2012; Borrego, Karlin, McNair, & Beddoes, 2013; Cooke, Gorman, & Winner, 2007; Fu, Cagan, & Kotovsky, 2010; Hsiung, 2012; Jensen & Wood, 2003). Next I explore relevant research on teamwork outside of engineering that may be applied to aerospace engineering.

The *Cambridge Handbook of Expertise and Expert Performance* (Ericsson, 2006) provides insight into expert team behaviors based on several research methods. The three most common research data collection methods are: observations in the field, simulation, and self-report. Further explanation of research data collection methods relevant to this study can be found in Section 3.10.3. Key behaviors of expert teams (military, manufacturing business, aviation flight crews, and healthcare, but engineering design teams are noticeably absent) are summarized from many research publications in Table 25.1 of the handbook, reproduced in Table 2.3.1 below. Some key desirable items here for the aerospace business include "make fewer errors", "make better decisions", and "greater chance of mission success", which are driven by having these nine behaviors listed in bold font.

Table 2.3.1 Reproduction of Table 25.1. Expert team performance effective processes and outcomes in (Ericsson, 2006).

Expert Teams . . .
Hold shared mental models
They have members who anticipate each other.
They can communicate without the need to communicate overtly.
Optimize resources by learning and adapting
They are self-correcting.
They compensate for each other.
They reallocate functions.
Have clear roles and responsibilities
They manage expectations.
They have members who understand each others′ roles and how they fit together.
They ensure team member roles are clear but not overly rigid.
Have a clear, valued, and shared vision
They have a clear and common purpose.
Engage in a cycle or discipline of prebrief → performance → debrief
They regularly provide feedback to each other, both individually and as a team.
They establish and revise team goals and plans.
They differentiate between higher and lower priorities.
They have mechanisms for anticipating and reviewing issues/ problems of members.
The periodically diagnose team "effectiveness," including its results, its processes, and its vitality (morale, retention, energy).

Table 2.3.1 continued.

Have strong team leadership
They are led by someone with good leadership skills and not just technical competence.
They have team members who believe the leaders care about them.
They provide situation updates.
They foster teamwork, coordination, and cooperation.
They self-correct first.
Develop a strong sense of "collective," trust, teamness, and confidence
They manage conflict well; team members confront each other effectively.
They have a strong sense of team orientation.
They trust other team members' "intentions." They strongly believe in the team's collective ability to succeed.
They develop collective efficacy.
Manage and optimize performance outcomes
They make fewer errors.
They communicate often "enough"; they ensure that fellow team members have the information they need to be able to contribute.
They make better decisions.
They have a greater chance of mission success.
Cooperate and coordinate
They identify teamwork and task work requirements.
They ensure that, through staffing and/ or development, the team possesses the right mix of competencies.
They consciously integrate new team members.
They distribute and assign work thoughtfully.
They examine and adjust the team's physical workplace to optimize communication and coordination.

The key behavior or skill relevant to this study from the above expert teams is "make better decisions". But how are those decisions are developed, presented, and executed? It is especially important to consider teaming as a factor in design because, according to Thunnissen's uncertainty taxonomy, teaming may introduce ambiguity and interaction forms of uncertainty to the design decision; expert teams' behaviors listed above may be strategies for managing uncertainty introduced by teaming. Also, what constitutes "better" decisions and how does an individual person or an engineer become better at making decisions?

2.4 Expertise of Decision-making in Design Environments

A key cognitive process in good engineering design is decision-making and justifying those decisions with evidence (Crismond & Adams, 2012). Dorst (2004, 2011; Lawson, 2009) presents the Dreyfus model of expertise in six to eight categories and summarizes the approaches to design practice associated with each category, shown in Table 2.4.1 below. The approaches to design practice may be considered here as the manner in which decisions are made by an individual designer. This research may add a fourth column to Table 2.4.1 with specific treatment of uncertainty as a function of level of expertise.

Table 2.4.1 Levels of design expertise, adapted from Dorst (2004, 2011).

Level of Expertise	Approach to Design Practice	Approach to Design Practice Description
Naïve	Choice based	
Novice	Convention based	Consider objective features of situation, follow strict rules from experts
Advanced Beginner	Situation based	Situational aspects important, sensitivity to exceptions to 'hard rules'
Competent	Strategy based	Emotional attachment, trial-and-error, learning and reflecting, selects relevant elements, makes plan
(Proficient)		Immediately see most important issues, appropriate plan, reasons what to do
Expert	Experience based	Respond intuitively, perform appropriate action straightaway
Master	Create new schemata	Dwell on success and failure, acute sense of context, openness to subtle cues
Visionary	Redefine field	New ways of doing things, new definitions of the issues, operating on margins of domain, paying attention to other domains

Atman and other researchers (2007; 1999) have examined individual designers at first year undergraduate, senior year undergraduate, and practicing engineers with greater than ten years' experience and peer identification as an expert in design. They compared five themes across the participants' age demographic using an individually-executed design problem for a playground. Key differences include the experts spending more time than students in problem scoping and in gathering information, but not statistically different in developing alternative solutions or in solution quality. The relevance of these studies to this study are a tendency among experts to delay a decision until there is sufficient information and the time on task required (ten years) to develop expertise as noted by peers.

It is appropriate to acknowledge "bad" decision-making and mitigation strategies in an aviation flight crew context as well for completeness' sake. Flight trainers have summarized and disseminated research work in psychology to help pilots acknowledge their unconscious biases and make more objective and safer decisions (Benson, 2015). Possible culprits of bad decisions include: *illusory superiority* (overconfidence), *optimism bias* (having previous successes elsewhere) and *confirmation bias* (ignoring data that contradicts a decision). Therefore, risk mitigation strategies include: a two person sign-off (reciprocal arrangement with an uninvolved but informed person), explicit risk assessment tools (numerical matrices and checklists, for example), and a personal minimums checklist, individualized to that decision-maker's aptitude and context. These same decision traps apply to engineers (National Aeronautics and Space Administration, 2011) and therefore a similar toolbox to mitigate bad decision-making in design may be necessary.

2.5 Skills: Managing Uncertainty

Managing uncertainty in design thinking is a necessary skill (Dym et al., 2005) among many. Good systems designers are characterized by thinking about system dynamics, reasoning about uncertainty, making estimates, and conducting experiments. Good designers tolerate ambiguity as part of divergent-convergent thinking. They think as part of a team. They communicate in several languages of design, including verbal/textual, graphical, shape grammars, features, mathematical/analytical models, and numbers. Good designers especially maintain sight of the big picture of systems design and systems thinking. Therefore, the use of the adjective "good" implies some distinct level of expertise in design, and by extension, some distinct level of expertise in reasoning about uncertainty.

In one example of different levels of skill in managing uncertainty, recent engineering education research has identified management of ambiguity as a facet of experience of design. In a phenomenographic context, the role of ambiguity in design may start as something to be eliminated, then something that is acknowledged as part of design, up to something welcome in design (Daly, 2008). The research results show that increasing acceptance of ambiguity is a theme with increasing experience of design; results are shown in Table 2.5.1 below. These results were generated across disciplines within and without engineering; design within the engineering discipline is the more pertinent topic, but these results are still useful as another model of increasing awareness and management of uncertainty.

Table 2.5.1 Reproduction of Table 4.4 in *Design Across Disciplines* (Daly, 2008).

Category	Role of Problem	Role of Ambiguity	Task endpoint	Goal of outcome
Category 1: evidence-based decision-making	It is set by someone else; there is no flexibility	Gather data to eliminate ambiguity	When evidence supports decisions the best	the best solution
Category 2: organized translation	Problem is set by someone else or self, but the designer discovers and adds new problems to be solved along the way	Tolerant but seeks to overcome where possible	When the solution achieves the goal and is satisfactory for all parties involved	Something that works
Category 3: personal synthesis		Tolerant	When the intention has been fulfilled	Achieve goal and expand repertoire
Category 4: intentional progression	Problem is loosely set at “start” and developed by the designer and stakeholders along the way	Just part of design	When it can be built upon	Something that can be built upon
Category 5: Directed creative exploration		An opportunity for new paths	When applications, new paths, and frameworks for guiding future work are evident	Something of value for others
Category 6: Freedom	Designer develops a problem to be solved	Cultivates it; transforms constraints to freedoms	Only when someone else takes it over; it always evolves when it is with the designer	Something with meaning for oneself or others

In a second example of different skills in managing uncertainty, within NDM environments, particularly studying military officers, researchers found a set of coping strategies for uncertainty (Lipshitz & Strauss, 1997). These tactics fall into five larger categories: reduction, forestalling, assumption-based reasoning, weighing pros and cons, and suppression. They conclude that different coping strategies accompany different types of uncertainty. However, they do not make assertions about decision expertise favoring certain strategies over others. Coping strategies may be considered a synonym for managing uncertainty.

If there are different levels of skill in managing uncertainty, then there is likely a way to quantify or measure skill level. Older research in psychology situates ambiguity in social situations mostly and somewhat in problem-solving situations in order to create a scale for quantifying tolerance (MacDonald, 1970; McLain, 1993). Newer scales for tolerance for ambiguity have been developed in business and have been operationalized as valuing diverse others, coping with change, managing conflicting perspectives, and dealing with unfamiliar situations (Herman et al., 2010). Aerospace engineering design businesses are still businesses, so Herman's scale may be useful. Related scales are being developed to measure risk attitudes (Van Bossuyt et al., 2013). However, to focus on design, development of a scale for tolerance for ambiguity in engineering design would requires this study's investigation of aerospace-specific content and context first.

2.6 Theories of Learning and Development of Skills

If management of uncertainty is considered a skill, then Skill Theory (Fischer, 1980) can describe the development of these skills in pursuit of answers to the future research questions of this work. In particular, Skill Theory asserts that a skill is developed only if the environment induces the learner to use the relevant content in a task, which is a Piagetian concept. Skill development is gradual and continuous. Skills can be hierarchically arranged because higher level skills require the mastery of lower level skills. Key vocabulary of Skill Theory is shown in Table 2.6.1 below.

Table 2.6.1 Key concepts of Skill Theory.

Keyword	***Definition***
Skill	Unit of behavior composed of one or more sets
Level	Skill structure of gradually increasing complexity
Set	Collection of things (cognition, action, and object that is part of the environment)
Map	Structure relating two sets
System	Relation between two subdivided sets
System of Systems	Relation between two systems
Tier	Skills of vastly different types
Sensory-Motor	Actions or perceptions on things or events in the world
Representation	Simple properties of objects, events, or people; independent of person's immediate actions
Abstract	Intangible attributes that characterize broad categories of objects, events, or people
Intercoordination	How the person combines skills to develop from level to level
Compounding	Microdevelopmental transformation to combine two skills at a level into a more complex skill at the same level
Focusing	Moment-to-moment change in behavior commonly called attention
Substitution	When a person attempts to transfer a skill at level to a similar task, changing one component of the task
Differentiation	When a person separates into distinct subsets something that was initially a single set

Uncertainty is abstract. According to Skill Theory, the abstract tier of skills is likely to be domain-specific, so it is the responsibility of the educators within the domain to discover the hierarchical arrangement of the skills through research. The practitioners and educators in the domain must uncover the content, the task, and the logical arrangement of these items for students. A generic representation of the outcome space is shown in Figure 2.6.1 below, where Fischer's original representation is in the bottom left corner and the center and right columns have been added for completeness.

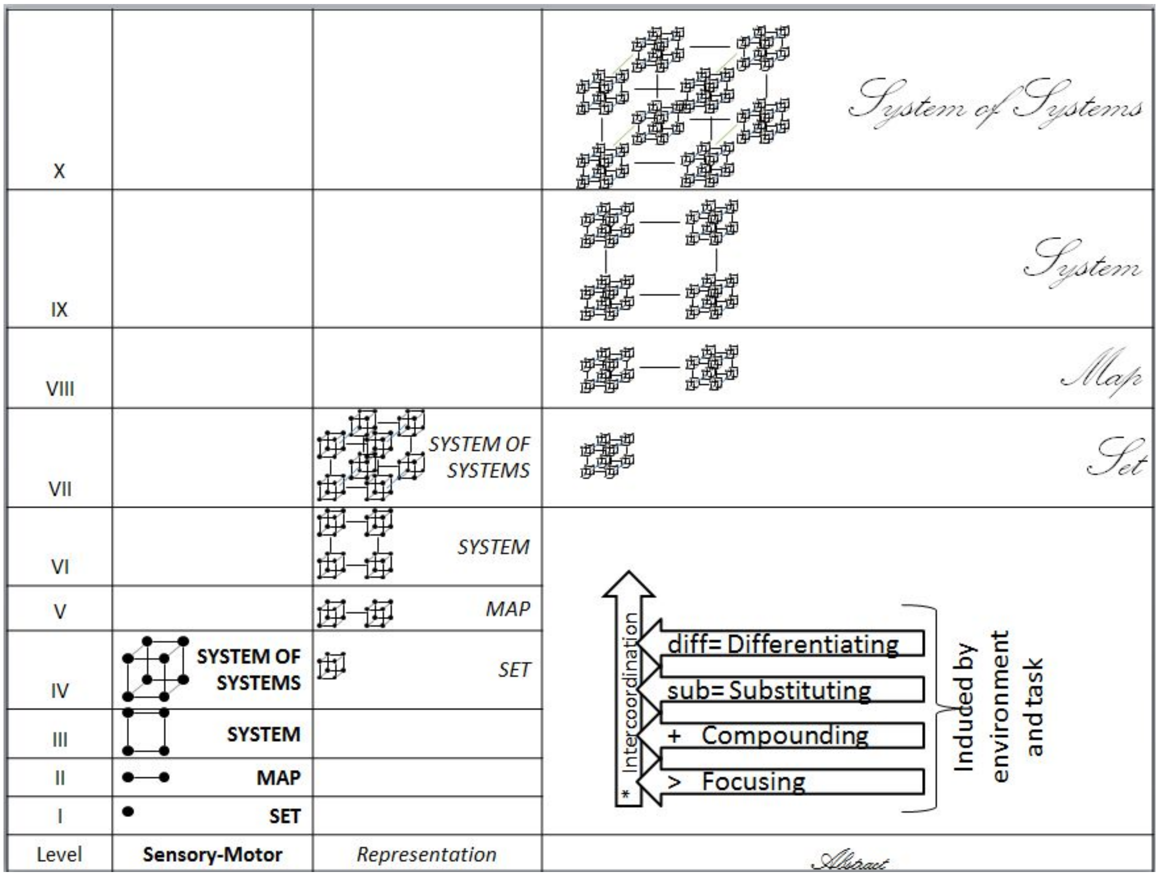

Figure 2.6.1 Fischer's Skill Theory: basic notation and visual metaphor of cycles.

Level VII is the starting point for Engineering Education research. Fischer describes the concept of conservation as first being understood by an individual at this level. For white middle-class Americans, Level VII thinking starts to appear in the early high school years. These are not hard and fast rules of human cognitive development, however; it has been shown that it is possible to have concrete learners as first year college students (Kalman, 2007). As an example of abstract thinking, "At Level 7, single abstract sets, a person can for the first time construct abstract identity skills", such as relating a father identity to a career identity as a psychologist. He also states "Levels 7 to 10 include moral judgment, the managerial skills… skills required to write an effective essay… skills involved in programming and operating a computer" so engineering sciences and engineering design fit in these higher abstract levels.

The transformation rules "predict specific sequences of development", which makes the theory exceptionally useful to Engineering Education research. Fischer found five but acknowledges that there may be more if future research suggests it. The transformation rules are represented in the bottom right of Figure 2.6.1, where the vertical arrow represents macrodevelopmental transformations and the horizontal arrows represent microdevelopmental transformations. Developmental change may occur in spurts, with rapid change at the beginning and slower change as the level has been developed, not unlike product development S-curves (Ullman, 2003).

Several concepts favored in Engineering Education are present in Skill Theory. Situated Cognition (Brown, Collins, & Duguid, 1989; Orgill, 2007) is a research theoretical framework that overlaps Skill Theory's emphasis on task and content as having a direct impact on which skills are induced to be developed. "Abstract systems-of-systems" is Level 10 in Skill Theory, which is very similar vocabulary to aerospace as systems-of-systems and global thinking. Like Vygotsky's Zone of Proximal Development (Vygotsky, 1986), "the person must initially have the skills required for application of the transformation and must be capable of applying the transformation rules to those skills" in order to develop the next higher skill. This is significant because it may provide clues on why the abstract systems-of-systems skill of managing uncertainty in design decisions is difficult or why it may take 10 years to develop.

2.7 Summary

The aerospace design industry, a system-of-systems hierarchy, produces products and services that operate in or are Large Scale Complex Engineered Systems. Uncertainty is ever present from multiple sources and is often operationalized by *risk*. Engineers in industry must have awareness of uncertainty and successful strategies for managing uncertainty in order to reduce risk to some socially-constructed acceptable level. Managing uncertainty and making decisions are necessary cognitive skills in design, and there is, at the moment, a binary spectrum of “bad” to “good” skill level. Skill Theory, built on Piaget’s constructivism theoretical framework, asserts that abstract skills can be learned by intercoordinating lower level skills through the performance of a particular task in a particular environment. Skills will vary because of various tasks and environments. Skills may even be distributed across a team instead of simply within an individual. But the particular tasks in particular environments (Johri & Olds, 2011) that specifically develop an increasing awareness of and tolerance of uncertainty as it impacts decision-making are not yet well investigated.

2.8 Research Questions

The existing literature cites many works examining design and uncertainty, but there are gaps. There are models of negotiating uncertainty in social situations, but not specific to the aerospace context as a unique culture. There are descriptions of the context of the aerospace business and Naturalistic Decision Making, but not specifically focused on managing uncertainty. There are descriptions of types of uncertainty in aerospace applications, but not accompanying management strategies. There are descriptions of levels of design expertise, but missing the element of managing uncertainty per level. There are models of learning, but not specific to learning to manage uncertainty. To fill these gaps and provide a framework to inform curricula and professional development programs, this research seeks to address these two primary research questions:

1. What are the qualitatively different ways that engineers in aerospace businesses experience uncertainty in design decisions?
2. How do aerospace design engineers develop successful uncertainty management skills?

The first set of questions above seeks to stratify the phenomenon of managing uncertainty in aerospace applications. The implication of having increasing levels of successful management of uncertainty implies that the skill can be learned and developed. Development implies the need for assessment to prove attainment of a level. Therefore, future research questions include:

3. How can Skill Theory be applied to engineering learning environments?
4. What are effective interventions and classroom modules that increase an aerospace engineering student’s ability to manage uncertainty in making design decisions?
5. How can an aerospace engineering student’s management of uncertainty in design decisions be measured?

CHAPTER 3. THEORETICAL FRAMEWORK AND METHODOLOGY: PHENOMENOGRAPHY

In this work, *theoretical framework* is akin to Kuhn's (1996) *paradigm* that guides the construction of the research questions, the data collection methods, and the analysis of a study (Bodner & Orgill, 2007). The theoretical framework informs the *methodology* (Case & Light, 2011), which is composed of the data collection methods and analysis of the data. A *conceptual framework* is defined in this work as the definition, description, and attributes of a concept or phenomenon under investigation, such as uncertainty as described by Thunnissen in Chapter 2.1. In other words, it is possible to investigate the conceptual framework of uncertainty using several theoretical frameworks, depending on how the research question is written and which attributes are the most important to study.

The following sections highlight the philosophical stance, goals, and accompanying methodologies and methods of several theoretical frameworks. The focus of this work is the Australian tradition of phenomenography as the theoretical framework of choice.

3.1 Comparison of Candidate Frameworks

There are several theoretical frameworks that could be employed in pursuit of an answer to the general research questions from Deshmukh (2010) in Section 1.2:

ethnography (Creswell, 2008), phenomenology (Bodner & Orgill, 2007; Patton, 2002), and phenomenography (Bodner & Orgill, 2007; Bowden & Green, 2005; Marton, 1986). The most appropriate framework would be sensitive to the attributes of uncertainty in design decisions as presented in the literature review. The attributes of interest are: development of the skill of managing uncertainty over time, variation of experience with uncertainty, operating in a Naturalistic Decision Making environment, and designing Large Scale Complex Engineered Systems. Table 3.1.1 below shows a summary comparison of the most likely frameworks and their sensitivity to the research question's attributes. The shadowed boxes in the table represent a mismatch.

Table 3.1.1 Candidate theoretical frameworks mapped to research question attributes.

	Theoretical Framework		
Attribute	Ethnography	Phenomenology	Phenomenography
Development of skill over time	Oriented towards beliefs rather than skills	Well-suited to describe a lived experience	Well-suited to describe a lived experience
Variation of experience of uncertainty	Typically focus on a group's shared experience	Goal is to find a single common meaning of an experience	Well-suited to account for variation
Naturalistic decision-making environment	Well-suited to describe the culture of aerospace *in situ* (observations in the field)	Well-suited to describe a lived experience (self-report)	Deep, open interview allows for reflection on environment (simulation and/or self-report)
Large Scale Complex Engineered Systems	Well-suited to describe the important artifacts of aerospace as part of the culture	Well-suited to describe the important artifacts of aerospace as part of the phenomenon	Deep, open interview allows for reflection on LSCES

The primary goal of ethnography is to describe a culture's behaviors and beliefs, and researchers have argued that the workplace is a culture worthy of investigation.

Ethnography has been employed to study the role of ambiguity and uncertainty in the progress of design (Louis L. Bucciarelli, 1994). Ethnography has been useful in studying the physical sciences and engineering as well (Case & Light, 2011; Coley, Houseman, & Roy, 2007; Dym et al., 2005; Latour & Woolgar, 1986; Rivas McGowan et al., 2012; Tonso, 2006). The aerospace business can be considered a unique culture, having a risk-averse attitude, having a shared language centered on aviation activities, and having a shared belief in the importance of teaming. However, its strength is identifying a common belief that transcends time, so it is not a suitable method for capturing individual learning through varied experiences.

Phenomenology primarily seeks to find a common essence in lived experience (Bodner & Orgill, 2007; Patton, 2002). A key element of selecting participants is that the participant did indeed experience the phenomenon under study. The primary objective is to find a common experience (the thing itself). In this work, the thing itself is uncertainty as described by Thunnissen's uncertainty taxonomy. Phenomenology is not well-suited to describing various experiences of the participants, where variation originates from organism, environment, and task as Skill Theory in Section 2.6 proposes.

Phenomenography accounts primarily for variation in experience by uncovering the relation between the participant and the phenomenon (Bowden & Green, 2005). The basic premise is that there are limited number of qualitatively different ways that a phenomenon can be understood or experienced (Marton, 1986). The interpreter of the phenomenon is the participant, not the researcher. In order to solicit a variety of experiences and to allow all relevant voices to be heard (National Commission for the Proptection of Human Subjects of Biomedical and Behavioral Research, 1978), a highly varied sampling of participants is necessary. With a proper semi-structured interview, the participant can unveil the environment, the products, and the processes of their professional experiences. The creation of hierarchical categories as part of the analysis may uncover the development of the skill of managing uncertainty. Therefore, phenomenography is the most suitable theoretical framework for the research questions in Section 2.8.

Phenomenography suggests a logical relationship among outcomes (typically a hierarchy) and Skill Theory suggests a hierarchical relationship of skills. Phenomenography is aimed at application to education; Skill Theory is also for the benefit of education. The human experience of developing the skill of management of uncertainty is likely varied, due at least in part to the varied nature of uncertainty in engineering design and decision-making. In other words, the idea of *experience* may include but is not limited to the variety and quantity of uncertainty in design, and may also include an engineer's various management strategies. Phenomenography involves semi-structured interviewing as the primary data collection method. The trade-off for long observations in the field or short observations around a problem-solving task then is open, deep interviewing as the data collection method.

3.2 Key Concepts in Phenomenography

The assumptions and the goals of phenomenography align with the assumptions and goals of this work. Phenomenography is purely qualitative and non-experimental. Correct and mistaken concepts of the phenomenon are equally interesting to the researcher, because "A careful account of the different ways people think about phenomena may help uncover conditions that facilitate the transition from one way of thinking to a qualitatively 'better' perception of reality" (Marton, 1986). The following subsections highlight the philosophical stance and goals of phenomenography as the theoretical framework of choice in this work.

3.2.1 Phenomenon

Phenomenon is defined from the Greek root word as "a thing as it appeared" (Richardson, 1999) instead of "a thing in itself". The epistemological and philosophical stances are described as "The object of study in phenomenographic research is not the phenomenon being discussed *per se*, but rather the relation between the subjects and that phenomenon" (Bowden & Green, 2005):

> Phenomenographers are among a range of qualitative researchers who take a non-dualist stance. We do not focus on hypothetical mental structures separate from the world. There is no dividing line between the inner and the outer worlds. There are not two world with one held to explain the other. The world is not constructed by the individual, nor is it imposed from the outside, 'it is constituted as an internal relation between them. There is only one world, but it is a world we experience, a world in which we live, a world that is ours'.

3.2.2 Outcome Space

Phenomenography as a theoretical framework and methodology typically has as its outcome an arrangement of categories, that is often hierarchical in nature, which are variations of human experience of a phenomenon. The outcome space often implies an increasingly comprehensive awareness or increasingly comprehensive experiences (Daly, 2008; Zoltowski, 2010). The outcome space has three attributes: simple and clear, logically related typically by hierarchy, and parsimonious or few (L. Mann, 2014). The outcomes must derive from the data and not from the researcher's preconceived notions or even from the published literature's results because the investigation focuses on the participants' understanding of the phenomenon. The goal is practical applicability, which is the goal in this work for engineering education.

3.3 Assumptions of Phenomenography

First, phenomenography assumes that there are a limited number of qualitatively different ways that people experience and understand a phenomenon (Marton, 1986). While there is no limit to the number of potential categories, it implies that the outcome space should include just a few categories. While "few" means different numbers to different people, recent engineering education outcome spaces generally do not exceed seven unique categories (Bucks & Oakes, 2011; Daly, 2008; L. M. W. Mann, 2007; Zoltowski, 2010).

Second, phenomenography makes no assumption of right or wrong interpretations, which would be some kind of interpretation from the researcher. This would include concepts about physical phenomena, such as velocity, for which there is a "correct" answer (Marton, 1986). Applying an assumption of what is right or wrong would unnecessarily limit the researcher's understanding of the participants' understandings.

Third, phenomenography does not assume a dualist view of the world as individual constructivism and social constructivism do. "Individual constructivism sees internal mental acts as being an explanation for external acts and behaviors. The reverse is true for social constructivism" (Bowden & Green, 2005). Rather, phenomenography assumes a relational view, a point of controversy to some critics in Section 3.8.

3.4 Propositions and Expectations

Phenomenography takes a stance of having no qualitative expectations. Rather, the researcher is bound to bracket him/herself from presuppositions and hypotheses, even from seemingly authoritative sources (Ashworth & Lucas, 1998). Ashworth and Lucas note that phenomenography suggests bracketing may go against the traditional tide of reviewing literature before conducting research in order for the researcher not to be biased. The researchers must bracket themselves (remove themselves from interpreting the phenomenon) (Marton, 1986). Bracketing in phenomenography derives from phenomenology's *epoche*, meaning "to refrain from judgment" (Patton, 2002). Since bracketing is almost humanly impossible, it is better to acknowledge biases, demonstrated in Section 3.9 below and to ensure reliability and validity.

3.5 Key Researchers and Their Perspectives

Original phenomenography, or the Swedish tradition, has been employed in order to understand students' conceptions of reality, including forces and optics, and it requires problem solving before interviewing as part of the data collection (Marton, 1986). As researchers have employed simulation techniques to expert teams (Ericsson, 2006), so problem solving in Marton's phenomenography could be considered a simulation in order to understand the participants' knowing. Observation of the participants' interaction with the phenomenon is part of Original phenomenography. Within a Large Scale Complex Engineered Systems context in Section 2.1, observation is not a practical data collection method for this application as the development times in aerospace can span many years.

Developmental phenomenography, or the Australian tradition, typically employs semi-structured interviews to elicit participants' reflections on their experience, where the intent is to seek depth in the experience (Bowden & Green, 2005). While original phenomenography and developmental phenomenography can be centered on learning, developmental phenomenography does not include the observation of the participant encountering the phenomenon in a problem-solving task. The literature review showed that the scale of the design environments being researched does not align well with original phenomenography because of the complexity of the problems that are encountered in aerospace design. A task that could fit into the timeframe of an interview would be a simulation and not an actual design, thereby introducing the question if the subject would really apply the same techniques to the real design. As a result, only the semi-structured interview in the Australian tradition was employed here. Table 3.5.1 below shows that the crucial difference between these two methods that affects this project is the alignment for NDM environments, where the shadowed areas indicate a mismatch.

Table 3.5.1 Two types of phenomenography mapped to research question attributes.

Attribute	Marton Original phenomenography	Bowden Developmental phenomenography
Development of skill over time	Well-suited to describe a lived experience	Well-suited to describe a lived experience
Variation of experience	Well-suited to account for variation	Well-suited to account for variation
Naturalistic decision-making environment	Prescribed design task or problem-solving is *in vivo* rather than *in situ*	Deep, open interview allows for reflection on environment
Large Scale Complex Engineered Systems	Prescribed design task or problem-solving does not align with time scale or complexity scale of aerospace	Deep, open interview allows for reflection on Large Scale Complex Engineered Systems

3.6 Observable Phenomena in Phenomenography

The primary observation is the relation between the subject and the phenomenon as the subject describes the phenomenon. The researcher brackets his or her own understanding the phenomenon and of the participant, but the researcher's deep, open interview technique causes the participant to reflect on the phenomenon richly (Bodner & Orgill, 2007). It should be noted here that the participant's description and the participant's actions may be different from each other; therefore, phenomenographers do not claim that they have uncovered a positivistic truth. Rather, researchers may claim that they have found something useful for education.

The primary phenomenon is the participants' varied experiences of uncertainty. Significant criteria for participant selection include the participants' education backgrounds, career trajectories, cultural experiences, and professional responsibilities within the larger scheme of their employers' relationships to one another. . The employing companies can be considered as having various levels within systems-of-systems, as in Section 2.2, such as a raw material supplier (D level), a subsystem supplier

(B, C level), an airframe integrator (A level), or a primary operator (OES level). The level at which a company operates implies different priorities in costs, qualities, and schedules, which in turn may become an uncertainty for others at different levels. The goal of this study is to include the maximum variation possible of the criteria listed here in order to achieve representative variation of the experience of uncertainty in design and decision-making.

3.7 Boundaries and Limitations

The boundaries of phenomenography are related to the data collection method of semi-structured interviewing of an individual, but not a group, a team, or a project. The participants reflect on their experiences, the account of which may vary from what a researching observer or another participant may observe. From Table 2.4.1, a competent designer begins to reflect on design (Schön, 1983), making meaning of their experiences. Experiences for which a person has deeply reflected may be communicated as a well-rehearsed speech, but first-time consideration to a topic may be communicated with pauses, *uhs* and *ums* (Buzzanell, 2012). To the extent of established trust and comfort, the participant will share experiences with the researcher (Rubin & Rubin, 2012). Within these boundaries and within the boundary of fatigue of the participant, responsibility rests with the interviewer to "dig deeply" into the participants' experiences.

There are several limitations to acknowledge because of the data collection method of semi-structured interview only. First, this theoretical framework moves the interpretive work from the researcher to the participant. Also, different researchers may converge upon different outcome categories with the same data. Second, what the participant remembers and how the participant remembers could be limitation. In learning, people tend to remember best the first thing, the last thing, and the most intense thing (Thorndike, 1932). The participants, as they tell their stories, are attempting to make sense of their experiences (Weick, 1995), and will therefore put certain aspects in the foreground or background as part of their narrative (Bruner, 1986; Buzzanell, 2012). Third, participant selection could be a limitation, to assume that the participants have indeed experienced the phenomenon under investigation. In developmental phenomenography, it is difficult to confirm beforehand without the researcher making some assumptions about the phenomenon and the participant. The key to addressing these limitations is ensuring validity and reliability.

There may be limitations in the results from several attributes of participants. First, self-selection of participants is unavoidable in the design of this study, generally based on their schedule, their interest, and whether contact information is available to send a recruiting email. This is especially pertinent in recruiting older female engineers in a business with significant gender disparity, where the women might be fatigued with frequent requests to represent the female population. Second, it is unlikely that several of the participants will have worked on the same project, so while literature shows that aerospace engineering relies on teams, it might not be demonstrated well in this study. Third, focusing on working professionals' experiences may limit the results' applicability to the undergraduate curriculum. As with many qualitative studies, top candidates for inclusion can be identified and whoever is willing will be interviewed.

There are some mitigating steps to address the limitations. First, including variation in participants' job titles and employing companies may indirectly influence variation of awareness of uncertainty. Some job ranks may be: first level supervisor, chief, director, technical fellow, and vice president. Second, thinking about systems-of-systems in Section 2.2, employing companies may be OES, A, B, C, and D levels. Third, regarding the applicability of professional experiences to curriculum experiences, the interview protocol has primary questions on the participants' reflections on their learning trajectories, so there may be evidence linking the two experiences. Fourth aerospace students in their last year of schooling can be included as the "starting point", though the participants' age is not necessarily directly correlated to level of awareness of uncertainty. Each of these mitigating steps has been included in this work.

The biggest limitation is the challenge of rigor (Sin, 2010) in developing the outcome space, especially to those who are purely quantitative researchers. The first mitigation is a member check and edit of the transcript from the participant, but not a check of the outcome space (Cohen & Crabtree, July 2006). The second mitigation is multiple readings of the transcripts as a whole after all the data are collected,. The third mitigation is team analysis that welcomes challenge, critique, and revisiting assumptions (Bowden & Green, 2005). The fourth mitigation is to be transparent in the data collection and analysis process; each of the steps of the process will be documented as appendices for further review by the research community at large. The fifth mitigation is to validate the results with other published literature, and to justify any discrepancies that may arise. After all of these steps, the outcome space is reliable and valid.

3.8 Controversies

Richardson provides a thorough critique of phenomenography, including its incomplete development as a research methodology and its increasing application in education (Richardson, 1999), as do Ashworth and Lucas (1998). Richardson claims that original phenomenography lacks a conceptual basis and epistemological foundation that other social-science research methods have, primarily compared to constructivism. He contrasts phenomenography's interviewing as shallower than ethnography's or anthropology's interviewing, especially because the analysis "depends on other people's discursive accounts of their experience". He shows phenomenography as being similar to grounded theory and phenomenology in analysis. The positive aspect of phenomenography is that the results are easily accessible by professors and students, so that pedagogy can increasingly be based upon evidence-based methods.

3.9 Researcher Biases, Role of the Researcher

In Section 3.4, one of the requirements of phenomenography is to bracket oneself in the analysis, or to not let biases mask key results in the study. Since that is a near impossible challenge for most humans, I will acknowledge the perspective I bring to this study instead. I am a half-white female engineer and pilot with industry experience, and I did not cope well with uncertainty for at least the first two years of my employment, and still may not, if imposter syndrome (Brems, Baldwin, Davis, & Namyniuk, 1994) is an underlying factor, which drives this research project.

I worked as an aerodynamicist on tiltrotor aircraft for seven years (A. Cummings, 2014). My supervisors and coworkers told stories of the development of the aircraft.

Books were published by authors on the outside, either enthusiasts or technology naysayers within the helicopter business. My coworkers ridiculed news articles that were fraught with inaccuracies. I participated in flight test, which was considered the truth source against which the mathematical models were measured, but experiments have their own uncertainties. It became clearer over time that no one person knew everything about this aircraft and that there are multiple stakeholders with conflicting priorities who have decision-making responsibilities and influence on the design. It is this lengthy experience that drives my research questions.

My industry experience may be a foundation of trust in recruiting participants. My connections to my former coworkers may build a pool of potential participants quickly, but perhaps not diversely. It may also impede my follow-up questions on word choices because I think I have the shared aerospace language but the participant may be thinking about a topic differently.

My industry experience may also cause me to have a laser focus on elements of the data that echo my own experience and I may ignore significant elements of the data that I did not personally experience. For example, I learned the Earned Value Management System, which tracks cost, schedule, and deliverables as metrics comparing planned to actual performance. Therefore, I realize that there are cost and schedule uncertainties in addition to uncertainties in making some design function according to specifications.

Another bias goes against the grain of the Engineering Education research agenda of diversity and inclusion ("The Research Agenda for the New Discipline of Engineering Education," 2006). Knowing that engineering has a persistent gender disparity, even exaggerated in the population of pilots (4% of the workforce (U.S. Bureau Labor Statistics, May 2014)) compared to engineers, I should make every effort to include a representative percentage female sample in my study. Yet, I have no personal evidence that competence with engineering skills or experience of uncertainty in design is dependent upon gender. Therefore, I do not wish to show in my study that a variable of interest is gender. I defer to my study participants, then, on highlighting whatever factors they think most significant.

My tendency to analyze qualitative data in fine and detailed cuts has its roots in my industry experience with quantitative data. Fine cuts of flight test data provide more independent variables for correlating the mathematical models, which have many interdependent variables. I would naturally opt for finer cuts of experience of uncertainty according to Thunnissen's uncertainty taxonomy in order to explain the outcome space. This tendency may be in direct contrast to the parsimony of phenomenographic outcome spaces.

Antidotes to these biases may be more than three iterations categorizing the transcript data and analyzing as a team of researchers (Bowden & Green, 2005). Records of each iteration of analysis are warranted as an appendix of the final report of this study, though only the final defensible outcome space merits a chapter. Iteration and collaboration with a larger research team ensures validity and reliability.

3.10 Methodology

Certain decisions for the method are driven by the purely qualitative methodology of phenomenography. The design of this study is non-experimental, so any changes of behavior or skill noted in this work are not the result of a controlled intervention. The data collection method is semi-structured interview only. The accompanying analysis will be the creation of categories of qualitatively different ways that the whole transcripts reveal of experiencing the phenomenon of uncertainty, where within a category, participants have commonalities, and between categories, the participants have distinct differences. I make no assertion, claim, or hypothesis at the start of data collection what those distinct differences might be, but only that there are unnamed differences.

3.10.1 Population

The population of interest is individuals who 1) earned an engineering degree, 2) have done engineering design as a part of their careers, 3) are empowered to make decisions and 4) are employed in aerospace businesses, whether in the US or abroad. It is implied from the literature review that if a person engages in engineering design in the professional workforce, then that person will encounter uncertainty of at least one type. Participants were also included who are upper level undergraduate aerospace engineering students to represent a starting point of professionals entering the workforce.

3.10.1.1 Sampling Frame

A sampling frame is a "source that identifies members of the population for purposes of possible selection" (Blair, Czaja, & Blair, 2014). The sampling frame includes employees of businesses for which the researcher and close acquaintances have connections, also called chain or snowball sampling. The aerospace businesses are those that are airframe integrators, primary operators, or those suppliers who directly identify airframe integrators or primary operators as their customers. The attributes of the potential participants include a job title that indicates design and decision-making responsibilities.

3.10.1.2 Purposeful Sampling for Maximum Variation

Women compose 52% of the workforce in the United States but only 9% of employed aerospace engineers are women (U.S. Bureau Labor Statistics, May 2014). Women were purposefully over-sampled to insure their voices were included in the data. In Figure 3.10.2 below, there are six female participants, also represented in red circles in Figure 3.10.4. Eight participants have connection to Bell Helicopter, see Section 3.9, but the majority of the participants come from other businesses.

Attributes of the participants are demonstrated in Figure 3.10.2 below. Job titles are reported according to the participants' descriptions during the interviews. Education parameters were also reported by the participants at the beginning of each interview. Military experience, pilot experience, and international experience were reported by participants as influencing factors and so are reported here.

Different companies have a level of Systems-of-Systems applied, where company websites for "About Us" descriptions were used in order to make an assignment. There are four main S-o-S classifications: operators, airframe and powerplant integrators, subsystem suppliers, and materials. Because of the variation of experience, researcher and undergraduate are added in Figure 3.10.2 below. The employers could be (or might not be) but are not limited to: the customers NASA, Army, Navy, Marine Corps, Coast Guard, Air Force, DARPA, FAA, and militaries of other nations; the large prime contractors Boeing, Lockheed Martin, Bell Helicopter, Sikorsky, AgustaWestland, Airbus, Eurocopter; propulsion suppliers Rolls Royce, GE Aviation, Pratt & Whitney, and Lycoming. Each of the prime contractors and propulsion suppliers have their "second tier" suppliers. Researchers could be but are not limited to top tier research institutions and universities. Some of the more experienced individuals merited being classified in two levels of S-o-S because of greater than five years' experience in two different levels, but the majority of individuals have one primary level.

Figure 3.10.2, Figure 3.10.3, and Figure 3.10.4 below show the morphological chart (L. M. W. Mann, 2007) of pertinent participant demographics. Figure 3.10.4 shows the chain sampling of 13 participants as my personal contacts, and 8 contacts as my contacts' contacts, and four contacts as recruits through a professional society roster. The five gray arrows are the researcher's personal contacts that did not participate but forwarded the recruiting emails. The participants all have pseudonyms assigned after the interview and member check of the transcript.

Interview #	13	14	21	24	2	4	15	3	10	17	20	22	16	8	9	18	1	5	11	25	23	6	12	19	7
Pseudonym	Silvia	Ross	Luciana	Diana	Miranda	Viola	Margaret	Philip	Vincent	Ronald	Oliver	Jacques	Edmund	Nathaniel	Stephen	Bernard	Curtis	Alonso	Frank	Duncan	Bertram	Joel	Malcolm	Peter	Abraham
Gender	F	M	F	F	F	F	F	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
Years in Workforce	1	1	2	2	3	3	3	4	4	6	7	7	10	11	11	15	16	16	18	22	25	26	28	32	34
SoS Level																									
OES																	x					x			
A&P Integrator				x				x	x	x	x		x	x	x	x		x		x		x	x	x	x
Subsystems																					x		x	x	
Materials																			x						
Research			x		x	x	x					x			x										
Undergrad	x	x																							
Job Title	senior design	senior design	research assistant	design engineer	post-doc researcher	post-doc researcher	research assistant	engineer	Propulsion system enginee	project engineer	lead flt test engineer	program manager	engineer 3	engineer 3	engineer 5	design engineer	corporate tech fellow	integration leader	process engineer	chief engineer	senior engineer	director	senior program manager	Chief Tech Officer	engineer 5
Degree	BS Aero eng	BS Aero eng	BS Aero eng	BS Elec eng	PhD aero eng	PhD aero eng	MS Info sys	BS Aero eng	BS Mec eng	BS Aero eng	BS Aero eng	MS aero eng	MS Mec eng	BS Mec eng	MS Mec eng	BS Aero eng	MS Av Sci	MS sys eng	MS Indus t Tech	MS Aero eng	BS aero eng	BS Aero eng	MS int'l mgmt	BS Elec eng	BS aero eng
Military																	x					x			
Pilot										x	x				x	x	x					x			x
International	x				x		x					x						x							
Interview Minutes	61	56	84	62	90	52	63	66	81	72	87	63	74	93	69	59	76	80	60	82	82	131	71	57	82

Figure 3.10.1 Morphological chart for actual participants.

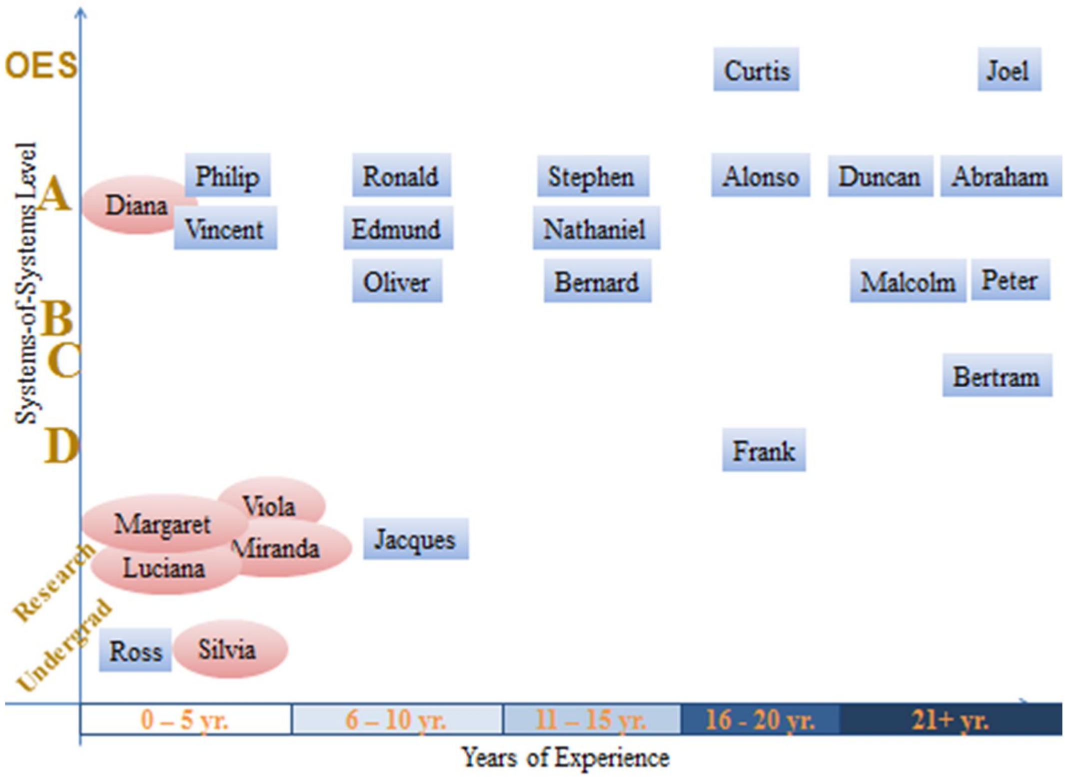

Figure 3.10.3 Participants' demographics of years of experience, gender, and systems-of-systems level.

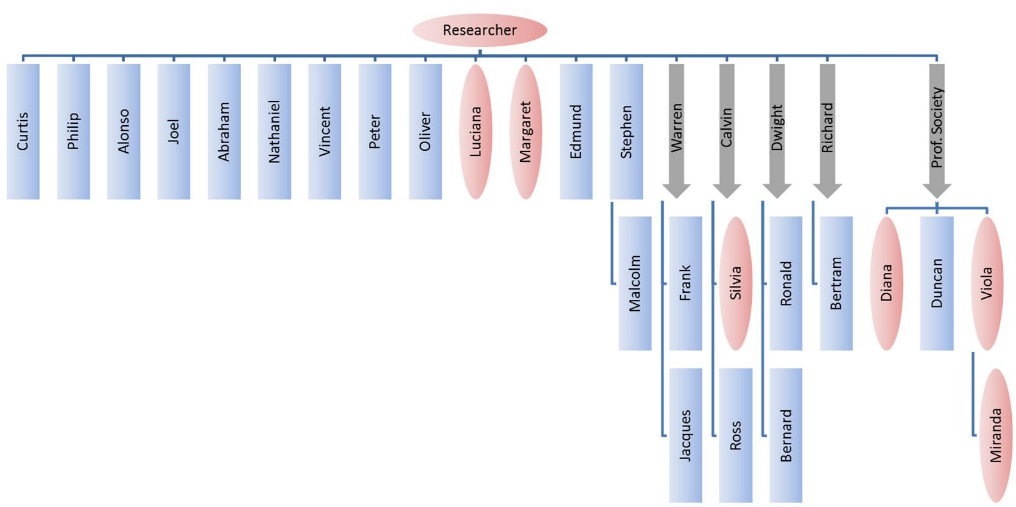

Figure 3.10.4 Chain sampling of actual participants.

3.10.2 Recruiting

It is typical to reach saturation around 20 to 30 participants (Bowden & Green, 2005) and it is more prudent to seek more than 20 interviews due to the anticipated variation of uncertainty. The reality of human research is willingness and availability of participants. Personal contacts were recruited first, with not more than two emails separated by two weeks. Actual participants were also asked to forward the recruiting email. Other personal contacts that did not fit the profile were asked to forward the recruiting email to any and all of their contacts that did fit the profile. Professional societies and clubs were asked to forward the email. At least 175 unique email addresses received the recruiting email from February to June 2015. The recruiting email for working engineers is in Appendix A.

3.10.3 Data Collection

3.10.3.1 Schedule and Budget

Time commitments and constraints for this study require some consideration. It is an appropriate plan to have a maximum of two face-to-face interviews a day to account for researcher fatigue, writing memos, and transcription (Rubin & Rubin, 2012), where the reality was one interview conducted per day. Because of conducting interviews online or remotely, travel for face-to-face interviews was not considered.

Transcripts were purchased through the vendor Rev.com at $1/audio minute, with about 33 hours of audio recorded in total. Six audio files were corrupted with excessive background noise, requiring me to transcribe them. The total expenditures for transcription were approximately $1,400.

Small incidental costs include purchasing a Skype phone number and minutes ($28), renting a Mac product to use FaceTime instead of Skype ($20), and purchasing an audio recorder ($40) which did not to have a USB port for file transfers, thereby making it less useful. Using a university software subscription for Camtasia to record audio/video of the Skype call and convert to audio only saved about $300.

After a one day turn-around for transcription, one cycle of analysis was reading and correcting the purchased transcripts. Transcripts were de-identified and emailed back to the participants, asking for a return with any corrections within two weeks. The majority of participants (16 of 25) complied, including one participant that requested a paper copy through mail.

Lastly, Figure 3.10.5 shows an ideal situation in blue of interviewing two participants a day, transcribing for one day, and sending out the transcript for a member check, where the red line shows actual data collection for this study. The positive slope represents completing an interview. The first data point represents IRB approval, and the next data point represents the first participant's interview. In between those two data points, for about one month, was the pilot study, in Section 3.10.4 below. The data collection effort for 25 interviews was about 5 months.

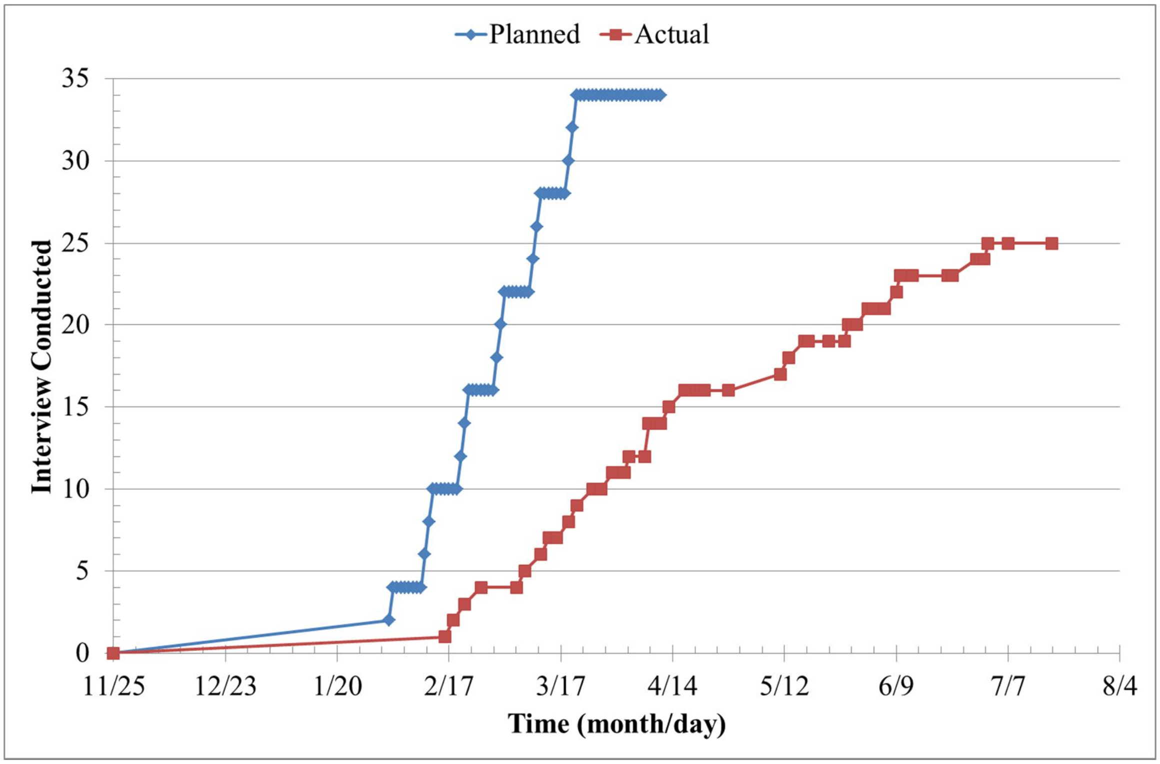

Figure 3.10.5 Planned and actual data collection for interview, transcription, and member check.

3.10.3.2 Instrument Development

A typical semi-structured interview protocol in phenomenography consists of contextual questions, open primary questions, situated example primary questions, and follow-up questions (Bowden & Green, 2005). Contextual questions provide an introduction and some understanding of a participant's current situation, encouraging the participant to reflect on their experiences. Open primary questions solicit the participant's understanding and meaning of the phenomenon. Situated example primary questions solicit concrete examples of the participant's own experience with the phenomenon. Follow-up questions encourage further elaboration of the experience, such as motivations and decisions related to the experience. Even though the literature review of CHAPTER 2 has many definitions of concepts and constructs, none of them are included in the interview protocol because of bracketing in Section 3.4.

Previously published work conducted provides some guidelines for constructing an interview protocol. One phenomenographic study of design was crafted to elicit participants' understanding of design, and the participants came from different disciplines (Daly, 2008). Another phenomenographic study focused on experiences in designing for others, or human-centered design (Zoltowski, 2010). A grounded theory study specifically asked working professionals about the problems they encounter at work (D. Jonassen et al., 2006). The grounded theory study provides questions to understand a participant's current workplace and responsibilities, and the phenomenographic studies provide questions worded particularly to elicit the participant's understanding of the phenomenon under study.

For this work, the contextual questions include the participant's workplace description, the participant's education, and the participant's current role in the workplace, including design projects. The open primary questions and situated example questions are the center of this work:

- The participant's experiences in making design decisions with uncertainty
- The participant's description of sources of uncertainty and the participant's management of identified sources of uncertainty
- The participant's reflection on the learning trajectory he or she experienced related to his or her awareness of uncertainty in design.

One aim of the contextual questions is that the participant's description of the workplace and his or her role within the workplace will match a Naturalistic Decision Making environment within a systems-of-systems environment. The open primary questions aim to uncover what participants recognize as sources of uncertainty, how to manage those uncertainties, and how they learned or became aware of those uncertainties. Follow-up and probing questions, highlighted in italics in Appendix B, will be asked if the participant needs prompting. Lastly, the aim of the entire project is to elicit words of wisdom from practicing engineers to upcoming engineers.

These questions were deemed exempt from human research governance in Appendix A. Minor changes not requiring review may be sent to IRB as an amendment to an approved study; however, in the execution of this study, no changes were necessary. The full instrument (interview protocol) is displayed in Appendix B.

3.10.4 Pilot Study

There are several reasons for pilot interviewing (Bowden & Green, 2005). I as the novice interviewer needed practice in setting a comfortable and natural interviewing environment. I also learned to bracket myself in the interview, avoiding comments and debates with the participant. Very importantly, the instrument needed to be tested for obtaining data on the intended topic, especially to see if there is variation in experience of the phenomenon. The recording media can be tested and note-taking for follow up questions can be practiced. I recruited several of my personal contacts for the pilot study.

Pilot study participants include individuals with varied experience at my home university. In the aerospace engineering department, there is a former Deputy Associate

Administrator of NASA. NASA may be considered an OES level operator in system-of-systems language. In materials engineering, there is a professor of practice with 30 years' experience. Materials businesses may be considered a□ level operator in system-of-systems language. There are also quite a few aerospace engineering graduate students, and one should be included in the pilot study. With just these three potential participants, there is variation in experience that may test the validity of the interview protocol.

The time commitment of the pilot study was one month. I transcribed the interviews for practice to test time to transcribe. Notes from the recorded interview were used for preliminary assessment of the validity of the protocol. Two iterations of the pilot study were scheduled as a good engineering design might include, but a second iteration was not necessary, so there are three pilot study participants.

3.10.4.1 Pilot Study Results

Per Section 3.10.4, the interview protocol of Appendix B was piloted in January 2015. One key difference in the pilot study was the ability to interview face-to-face rather than using online meetings; otherwise, the pilot was conducted as planned to conduct the full study. The objectives were fourfold:

1. Determine the effectiveness of the interview protocol for uncovering how a person experiences and manages uncertainty in design in an aerospace engineering context.
2. Provide practice for the researcher as an interviewer.
3. Investigate the alternative of conducting the interviews online or remotely.

4. Begin to uncover characteristics of participants that lead to greatest variation of experience with uncertainty.

The study started with individuals who are geographically close to me. Professors of practice were contacted for face-to-face pilot interviews. A graduate student with an aerospace engineering undergraduate degree was also contacted. Two were acquaintances and the third was recommended by an acquaintance. The primary characteristic of variation among these was years of experience. The professors of practice have worked in industry for more than 30 years; the graduate student worked for less than two years.

Per semi-structured interview, I practiced staying engaged with the interviewee's line of thought as I asked more questions from the protocol. Two of the interviews were about one hour; one of the interviews was almost two hours. It happened that the professors of practice drew diagrams and sketches on their available whiteboards in their offices for about five minutes of their interviews, while the graduate student did not create any visible artifacts or significant gestures during the interview.

Immediately following the second and third pilot interviews, the interviewees were asked if they felt comfortable in the interview and whether they felt that I listened to them or interrupted their thoughts. They reported that they felt comfortable and that they had the full opportunity to say everything they wanted to say.

3.10.4.2 Pilot Interview Summaries

Interviewee 1 views uncertainty as an everyday occurrence in the job, though he did not view himself as a designer broadly. His role as a director in the company was a "buck stops here" decision-making job. In Systems-of-Systems description, his company is a base level raw materials supplier. He told a story about investigating a design specification that he was certain could not be achieved by his company or any of its competitors. He was puzzled, then, as to what party defined that specification. He continued to ask questions until he found the designer in the Airframe & Powerplant Integrator company who admitted that "I just didn't like it" and wrote this unachievable specification. Interviewee 1 recognizes that uncertainty exists all the time and he seeks to reduce it through continued communication with other parties.

Interviewee 2 views uncertainty as an everyday occurrence in the job, that his company's role is to explore the unknown, to do things no one else has done before, and that is the fun challenge of the job. His company, as an Operational and Environmental Scenario level in Systems-of-Systems, managed Airframe & Powerplant suppliers and was subject to major political shifts and hidden agendas. His decision-making roles included Director and above. He told a story about the hidden political agendas being the greatest unknown on whether a certain project could even begin, and he was confident that the technical parameters could be met within the desired budget constraints. He also described that budget constraints play a larger role in deciding on designs than the phenomenological ("state of the art", not a research methodology) uncertainty of operating in an unexplored environment, which was not the case 40 years ago. Overall, Interviewee 2 recognizes and manages uncertainty from multiple sources.

Interviewee 3 recognizes uncertainty in design, including not knowing what process to follow, not knowing what resources to leverage, not knowing which questions to ask of experts, and uncertainty in cultural differences. From her senior design experience, the team struggled because they did not know of a process to follow and they did not know where to start, though they knew the end result was to have some device to participate in a competition. This experience was frustrating and the uncertainty regarding a design process was "debilitating". She told another story of taking a class in her master's degree that culminated in an international trip, which both made her aware of and comfortable with cross-cultural differences. Interviewee 3 recognizes some sources of uncertainty in design and is beginning to develop management strategies for some of those forms of uncertainty.

3.10.4.3 Strengths and Weaknesses

The achievement of the objectives is assessed here. Firstly, from the above summaries, it seems that the interview protocol collects the intended data, namely, variation of a person's experience and management of uncertainty in aerospace design. Other follow up questions to investigate motivations should be included:

1. Why is that important?
2. What were you trying to achieve by doing that?
3. Why was that difficult (or other word the participant uses)?
4. Can you think of an experience that prepared you to handle things you don't know?

Secondly, from the post-interview interviews of two participants, it seems that my interview technique is adequate and possibly improving. The participants reported felt comfortable and felt like they had a voice. The older participants appeared to have forgotten that the recording devices were present. However, the younger participant mentioned the fact of being recorded even as far as half way through the interview. The transcripts were provided to the participants for their opportunity to edit.

Thirdly, the evidence in the three interviews suggests that the desired data is primarily in the audio trace of the interview. The participants infrequently used gestures. Two participants drew pictures to illustrate their points, possibly because the room included a large writing space. One participant referenced documentation filed in his office in order to refresh his memory. One participant had a sample part of poor quality to illustrate the ambiguity of written test requirements. In all these instances, I took notes and drew similar sketches for future reference. The substantial verbal evidence collected here suggests that online or remote interviewing will not hinder data collection.

Lastly, the significant characteristics highlighted here that may affect a person's experience and management of uncertainty include: years of experience and job title. The higher job titles may indicate an increasing level of expertise in and responsibility for decision-making. Higher job titles may also indicate more opportunities to interact with other stakeholders in design. There is not yet enough evidence to support a gender difference, but there is room in the study to investigate this further. These key characteristics guide future purposeful sampling of participants for maximum variation.

3.10.5 Analysis

3.10.5.1 Method

Phenomenography can take at least two paths of analysis: 1) place the whole transcript into a category or 2) extract the quotes specific to the phenomenon into a category. In this work, I decided to place the entire transcript into a category. This is because the protocol is structured such that the beginning questions on design necessarily situate the experience of uncertainty within that design project. Therefore, most of the transcript focuses on one design project. Either way, "In the analysis stage, the controls involve:

- The use of no other evidence except the interview transcripts
- The bracketing of the researcher's own relation to the phenomenon
- The use of group analysis in order to ensure the first two controls are effective, and
- The analysis of the structural relation between the categories of description being postponed until after the categories have been finalized." (Bowden & Green, 2005).

3.10.5.2 Unit of Analysis

The unit of analysis in developmental phenomenography is the whole transcript, fit into a category. The researcher must be careful to say that the transcript and not the participant fits into a category, because it is unjust to categorize an entire person in only a two hour conversation (L. Mann, 2014). Transcripts within a category have marked similarity to each other, and categories must have qualitative differences among each other.

There are factors to consider in analyzing the data, according to the literature review. Firstly, there may be a range of responsibility for managing uncertainty, from individual to distributed responsibility across a small team, even up to a whole company. Secondly, at any systems-of-systems level, all of the participants are likely describe themselves as functioning in a Naturalistic Decision Making environment, though they may not use these words directly. NDM factors include organizational goals and norms, so it would be good to capture the influence of the levels at which the participants operate in complex systems-of-systems. Thirdly and most importantly, the level of awareness of the different sources of uncertainty for each participant is the driving factor of the outcome space.

3.10.6 Outcome Space

The outcome space of this study will primarily include some description of an individual's awareness and management of uncertainty. It is possible to use Dorst's levels of expertise in Table 2.4.1, but not so early in the analysis that it violates the first and second principles of analysis in Section 3.10.5.1 above. It is possible that the outcome space will have one, two, or three dimensions, but it would be difficult to visualize more than three axes of variation. More than three dimensions of variation may indicate another iteration of analysis is necessary. A category will have participants with common experiences, and different categories will highlight different experiences.

The resulting categories shall have substantiating evidence only from the transcripts (L. Mann, 2014). Each category will have a name or *handle*, hopefully condensed to one word. There will be a one sentence description. Following will be a few paragraphs of researcher interpretation, including supporting quotes from the transcripts in that category. Also, as mentioned in Section 3.2.2, the categories should be few, clear, and logically related.

CHAPTER 4. RESULTS: WAYS OF EXPERIENCING UNCERTAINTY IN DESIGN DECISIONS

The analysis resulted in identifying five categories of experience of uncertainty in design decisions. Several key pieces of literature provide the vocabulary to describe these resulting categories. The categories are shown graphically in Figure 4.5.1 with the horizontal axis indicating forms of uncertainty based on Thunnissen's taxonomy. The second vertical axis represents skill in team engagement, where the elements of expert teams in Table 2.3.1 are identified. There is a third dimension of the participants' responses to uncertainty by which the categories are named.

Even though phenomenography has no expectations or propositions at the beginning of a study, it is still essential to the analysis that the outcome space refers in some way to the phenomenon under investigation. Therefore, there is a necessary dimension of uncertainty in the outcome space. There is also a dimension named here as *response to uncertainty*, where in the preliminary stages of the study, I called it *management of uncertainty* as an answer to the second guiding research question of this work.

The most surprising dimension of experience is the pervasive response "talk to people" to the protocol question "what was your process for making those decisions", which upon analysis, I developed into discrete team engagement behaviors. Even though

I presented expert teaming in Section 2.3, I did not specifically ask or lead the participant with any of the identified team behaviors. Since participants specifically elaborated on talking to other people, it must be represented in the outcome space.

4.1 Process of Analysis

The execution of data collection and analysis merits a brief description here for reliability and validity purposes, with further details of the iterations of analysis provided in Appendix C. The first cycle of familiarization with the data after obtaining transcripts from a third party service was accomplished by my listening to the audio and correcting the transcripts. The corrected and de-identified transcripts were sent to the participants for any and all edits they wished to make; 16 of 25 participants returned edits and comments. These member-checked transcripts and the other transcripts appear in the final analysis.

I alternated between electronic and printed versions of the transcripts, keeping the electronic versions as the full archival record of my analysis. I printed, read, and highlighted paper copies of the transcripts. The handwritten notes and memos were transferred into an nVivo10 project. I put paper copies of transcripts into groups; I created nodes for the groups in nVivo. I wrote memos explaining similarities and differences among groups of transcripts. I shared the groups and memos with another researcher familiar with aerospace and phenomenography for further review, questioning, and perspective. As the appendix shows, I conducted at least 13 iterations of categorization before converging on the final results shown here.

Part of the evidence of having reached a valid outcome space is that subsequent cycles of analysis result in the same groups of transcripts (Bowden & Green, 2005). After 12 rounds of creating categories, the same transcripts converged into clusters for each perspective considered. The second piece of evidence is that the explanations of categories were reviewed by another researcher and found to be logical and consistent. A third piece of evidence, though less emphasized in phenomenography, is that there is no obvious and unjustifiable contradiction in this outcome space with other published literature. The reliable and valid results are presented as common elements and varied elements in the sections below.

4.2 Themes Common to All Participants

The main objective of phenomenography is to identify difference of experience, whereas the main objective of phenomenology is to identify the common experience. Because of the common context of the aerospace industry, there are common elements to all transcripts. Several of these items were delineated as the context of the study in the literature review CHAPTER 2. These common elements help to describe the backdrop of each participant's story, which backdrop is mostly a Naturalistic Decision Making environment as presented in Section 2.2.

The aerospace field is data-driven, including negotiated and written contracts with tangible requirements and specifications. The participants describe alternating between "big picture" and "smaller pieces" as they work through problems, leaning towards a systems thinking view of requirements to product design (Defense Systems Management College, 2001). The top three are cost, schedule, and performance, where performance cannot compromise flight safety. The matter of flight safety and cost align with the aspect of high stakes in Naturalistic Decision Making environments, and the matter of schedule aligns with the aspect of time stress. Because of these major criteria, engineers are encouraged to document lessons learned, and they encourage each other to learn from failure as well as success, touching on the research questions posed by Deshmukh in Section 1.2.

The corollary of being data-driven is the expectation that most things have been tried before; it is just a matter of finding the data or the analogy so that the engineer can set the expectation or the baseline. The participants describe documentation review as a key part of the design process. Having a baseline helps participants apply structure to ill-structured problems in a Naturalistic Decision Making environment.

The participants describe review cycles where they genuinely want someone else to validate their work. First, the engineer does his/her own work. Second, the engineer seeks an informal peer review. These two steps may be iterative between themselves. When the engineer converges on a decision with conviction, then the engineer is ready to present to their bosses or team leaders formally. This element aligns with the aspect of having feedback loops and having multiple players in Naturalistic Decision Making environments. Since these all are common elements, the following sections below will highlight the variations of the participants' experiences.

4.3 Categories of Description

The metaphor of materials' responses to stress (Callister, 2000) is used here to name the categories, symbolizing an internal response of the engineer to encountering uncertainty. Brittle materials fracture rapidly without appreciable macroscopic deformation. In other words, brittle materials have a dramatic reaction to stress. Plastic deformation is permanent or non-recoverable shaping after a load has been applied and released. In other words, a plastic response moves one way and stays that way. Tolerant materials do not fracture quickly under stress and are also called “forgiving”. Robust (Park et al., 2006) materials are ready for the load for which they have been designed and will perform well. Resilient materials have the capacity to absorb energy when deformed (Callister, 2000). In other words, resilient materials can recover quickly (Hollnagel, 2011).

The participants are grouped by their similar responses to uncertainty and the groups are aligned along two dimensions representing the other aspects of the participants’ experiences that differentiate them from one another. The first dimension is the complexity of the design tasks they undertake, as indicated by the quantity and quality of forms of uncertainty they are aware of. The second dimension is their skill at engaging their teammates and other stakeholders as they work through design tasks. The engineer’s internal response to uncertainty is the unifying dimension. So, there are three major aspects to each category of description.

I describe each category below by discussing each of the three aspects of their experiences. There were three primary questions explored with the participants in Section 3.10.3.2. They were: 1) an experience of decision-making in design; 2) experiencing uncertainty in design; and 3) reflections on learning about uncertainty. Example quotes from participants of each category are provided to illustrate each particular way of experiencing uncertainty. For uniformity of flow, quotes of each transcript will present significant themes of experience elicited by the primary questions: 1) forms of uncertainty; 2) team engagement; 3) personal response to uncertainty; each category is summarized with participant reflections on personal growth in managing uncertainty. The following sections answer the first research question in Section 2.8.

4.3.1 Category 1: Brittle

The first category is named Brittle. The engineers in the Brittle category are uncomfortable with uncertainty and their teaming mechanism is to push the decision responsibility to someone else, typically a boss or team leader. Their being uncomfortable with uncertainty can also manifest as being afraid of the consequences of being found ignorant by their superiors. The form of uncertainty these engineers experience is only epistemic, where they are aware that there is subject matter that they have not yet studied. This aligns well with Baillie and Johnson's findings that fear of uncertainty is a reason that knowledge may be troublesome to some learners (Johri & Olds, 2014). The tasks they have undertaken are typically managed as individual work and possibly soliciting informal peer review.

Negative emotions frequently appear in these transcripts, some of it stemming from an unsuccessful attempt at engaging stakeholders in the design and associated decisions. The level of support and attitude of their bosses or team leaders is highly influential on the emotions these engineers expressed. Unsupportive leaders cause the engineer to hold a negative view of the project while supportive leaders cause the engineer to have confidence in themselves and the completion of the project. Yet the engineers in this category have all completed assigned tasks satisfactorily.

The participants whose transcripts compose this category are Margaret, Philip, Ross and Silvia. These participants are primarily speaking from the experiences of senior design projects or internship design assignments. Two, Margaret and Philip, are in their first full time assignment and included those experiences.

4.3.1.1 Forms of Uncertainty

The participants whose experiences categorized the Brittle group only identified epistemic uncertainties. In particular, the participants describe ignorance of subject matter that they think is crucial to the success of their design projects. Partly, the ignorance may be perpetuated by another stakeholder's apparent unwillingness to share this information, thus linking the participant's personal response to uncertainty to someone else's influence.

For Margaret, the largest uncertainties in her research project are understanding her customer's needs, which even her customer had a difficult time defining, and obtaining the customer's historical data in order to validate and verify any new models she may develop. She considered her possible solution space as borrowing models from other disciplines, but her unfamiliarity with what other disciplines have developed has hindered her progress. Her solution paths, or her uncertainty management strategies, include what she describes as a randomly organized literature review, presentation to her immediate boss, and presentation in professional conferences for feedback. She said:

> When I do my literature review actually it's more random… It's kind of you start it very random. Then you find something interesting or closely

> related to what you're doing… Then you do some more reading about this. My difficult part is I have hard time to set the stop line of your literature review…Then my adviser tells me, 'Okay, you can stop now. You can just do this.' At least he will give me a deadline... I need some external power to let me make the decision more efficiently. The conference is also another external power for me…since the conference is coming I need to have something to have stop those random literature review and I need to think of what my work is.

Philip's industry experience has included flight simulation, flight test, and manufacturing. Philip had two primary epistemic uncertainties for his simulation task: "to be able to do it on time" and "to be able to do it at all". Philip described how he decided what coding language he would use to create a simulation model:

> Some people still love Fortran. You just have to ... It's all good. You can do it in Simulink, and it will be fine. You can do it in C, and it'll be fine, but I prefer to do in Simulink, and he prefers to do it in C, so you just have to argue a little bit. Then ultimately, whoever yells the loudest usually gets the final say in things like this, because this is a lower level thing…I've already started on it, and this is what we're going to do. I put my foot down. Sometimes you've just got to talk over the guy.

Ross, currently a senior design student, primarily spoke of one of his internship experiences. His task in his internships was to automate data acquisition in the laboratory. He described his problem solving process as “trial and error” and “you’ll get a problem and just be completely overwhelmed... break it down into sections that seem more manageable”. He saw two solution paths: “really advanced costly accelerometers for vibration, as well as just cheap Arduino do-it-yourself”.

He described his decision based on individual work: “I came to the conclusion that I would just do it myself, plus that way if there were issues, I would know, I wouldn't have to wait for someone or go through anyone…I would be the one fixing it and knowing everything about it.” His work was successful: “As long as they didn't touch the code, they were fine. They were pleased with it just because at the end, he told me honestly he didn't expect me to finish it.”

The uncertainty in this design task was “all of it”. He said:

> I came into this knowing nothing about this specific programming area, circuits, I've never worked with Arduinos…It was a daunting task at the beginning because I was uncertain about the whole thing. I've never done this, I broke it down a lot… I didn't realize the Arduino has a little community in itself… each day, there was a tiny little accomplishment or large frustration…It was more about what I could do and learn in the time frame then the best, not always the best solution but what worked for me at the time…I've never finished a project and say okay, I can explain 100% of what's happening here and we're done with it…I've never finished a project and say okay, I can explain 100% of what's happening here and we're done with it.

Silvia's responsibility in her senior design project was an opportunity to explore emerging technologies as potential components of the final solution. She spoke generally about keeping a customer in mind, about managing a budget and schedule to finish the project, and about the trade-offs between the technical parameters of batteries' weight to power density. But as for these new technologies, she had epistemic uncertainty:

> Sometimes when we look into internet and we see a lot of theory that's available to us, we only see the good sides because when a company is trying to put a product into the market, not every bad aspect ... industry secrets they would not let us know…Sometimes we look at the technology and wonder why they haven't been installed and why they haven't been used already because it sounds so perfect, but then if you do more delving and more research and you talk to people specially your professors or your TAs, you got to know that, oh, there's the side effect to the technology.

4.3.1.2 Team Engagement

Participants here tend to start work individually, and seek help infrequently. Participants here tend to see their team leaders as judges to whom they must show and defend their work. In this category, participants accept the relationship that others, whether bosses or team leaders, are final decision-makers on their work.

Margaret's team engagement is informal and infrequent, but she notes an improvement. She said: "I usually discuss with my group mates. I don't know why but at that time I get afraid to discuss with my adviser. Then last year, yeah, last year, I discuss more with my adviser."

Philip described his process for management approval as moving from casual to formal conversations:

> You feel good about this decision. Then you try to defend your choice. If other people can't shoot it down, then that's it and you're going to make this choice…I talked at them about it, and I bugged them about it, and I talked to them some more, then used a lot of hand gestures… It's like grassroots. You've got to build it up. You've got to get people on your side. Eventually, there's going to be a design review. Then that's like the formal decision where you've got to speak in business talk to people. But before that, you try and convince everybody that you've got the right idea. That's casual. You can be standing in line, like at lunch.

As Ross described his aerospace senior design project, he noted that his senior design team's responsibilities did not require him to make decisions. His task was "most of the sizing code in terms of figuring out what the weights are, what numbers need to be, not so much trade studies…I'm not doing a lot of the actual physical choosing the exact designs". His investment in the project's success he described as "NASA won't see anything until the final week of the project, but throughout, we all are doing presentations and just for the grade…We want to do the best as we can but the NASA thing is just an extra bonus, if ours is the best, I don't know what comes of it."

4.3.1.3 Personal Response to Uncertainty

Participants in this category described a strong link between their feelings about uncertainty in the design to their leaders' perceived feelings. Participants also have waves of positive and negative feelings as they progress through their design projects. If they perceive that something is not going well, at least according to the supposed judge or decision-maker, a negative feeling can be quite apparent.

Margaret described her personal experience of uncertainty as a process of emotions. She said:

> You're afraid, you have the fear. You have something, probably there's something unknown that will completely destroy your research. It might mean your research don't make any sense… You kind of reject it; you kind of unconsciously then you have to gradually just accept it…I discuss more with my adviser…you have more confidence to okay, he's good with it ... Feedbacks from group member they're also good. Sometimes it's very diverse. You cannot address all of them…I feel like I'm more of risk averse.

Philip described his personal response to uncertainty as an emotional cycle as he moved through his design project in a trial and error fashion:

> It would take too much money and too much time to go back and redo it, so it will be what it is… didn't know if it was going to work or not…you just face the consequences of it and afterwards you find out what happens…Part of it was acknowledging the fact that if it didn't work, then

> you're going to have to push the schedule back, and the company's going to lose some money. Then I'll probably get fired. That's the mental part of it…You just get thrown into the mix, and then you've got to learn things as you go, which is the [company] way. They throw you in, see if you can handle it.

Silvia described her strategy for managing uncertainty as soliciting judgment calls from her superiors:

> I think uncertainties are inevitable in a design…the only way to do it is to test it and the only way we can test a conceptual design is by talking to our professors…I think the only way to deal with uncertainty is to rely heavily on people who are experienced… Like [professor1] who is working with us on senior design…seniors who graduated and who are actually working in these industries…usually TAs have a lot of internship experience…go into companies like Boeing, Lockheed, Airbus, so we get a direct review of our product from the people who are already in the system and who are already working with these products.

4.3.1.4 Reflections on Learning to Manage Uncertainty

All participants were asked to reflect on their growth in ability to design, but only Silvia had a marked opinion. Like Margaret, Silvia explained about gradually accepting uncertainty will be present and cannot be eliminated. She has gained some theoretical knowledge from systems engineering classes: “I think when we deal with uncertainty when we were taught in the class was to make a fail-safe design. Even if you fail, you assume that you're going to fail but you're going to have something so that you know that you're going to fail safely.” For now, Silvia described her personal response to uncertainty as growing a little from life-changing events:

> I hate uncertainties, personally, because I have always like things planned…I think moving from a different country to the United States… being by myself was a big way of knowing that life is full of uncertainties and you need to just work through it…you're allowed to have these ideas and you're allowed to dream... You're made to believe that you can achieve anything…gave me a lot of confidence that there are things that you need to say you believe in and then prove that you believe in it and why you believe in it.

4.3.2 Category 2: Plastic

The engineers in the Plastic category find comfort in the “fact” that most things in aerospace have been tried before, so they just have to move in one previously-proven direction to finish their design tasks. Because of their adherence to a single solution path, their behavior may look like design fixation (Gero, 2011). They acknowledge that they are young so there must be someone more experienced to assist them as they explore the design solution space and make decisions. These engineers take some initiative to gather new knowledge as identified by more experienced engineers. They take a cycle of decision-making to justify their solutions to themselves first, or to convince themselves first.

They present their solutions to their bosses and team leaders for further review because they are beginning to view projects as team efforts, but it is a limited view. They acknowledge that other engineers have unique and complementary knowledge. They solicit peer review. They especially solicit Subject Matter Expert opinions and they do not demand data-driven justification from the SMEs.

Plastic engineers encounter epistemic uncertainty, such as topics they have not studied before. They also describe the new responsibility of creating or predicting schedule and budget of projects. Technical, cost, and schedule knowledge for Plastic engineers is best discovered by asking others directly to provide their opinions and to continue on the trajectory suggested by this resource.

The participants whose transcripts compose this category are Bernard, Diana, Edmund, Luciana, Miranda, and Vincent. Luciana and Diana have the least amount of experience at two years. Bernard has the most years of experience in this category; he hails from the pre-space-flight era of aerospace engineering but made a career change out of aerospace into self-employed handyman services after about 15 years, due to his uncertainty of the financial situation of his aerospace employer.

4.3.2.1 Forms of Uncertainty

The participants whose experiences categorized the Plastic group identified epistemic uncertainties as the Brittle category did, but with added schedule and budget impacts. The Plastic group, compared to the Brittle group, has a quicker tendency to ask others about these uncertainties, since they presume that the more experienced coworkers or the ones who went before them have correct insight into these uncertainties.

Bernard's transcript included four unique design experiences where he was given the task, he made drawings and prototypes, his idea was approved by his management team, and the idea was implemented with no apparent iterations or problems. His tasks were executed in a linear design process from problem definition to implementation. Bernard seemed to be sufficiently competent at designing that none of his ideas needed revision, so the "trial and error" mentality resulted in no errors. One of these experiences occurred over a very short time frame:

> There was a change in hydraulic systems of the airplane. One afternoon, the panels, the switches, had to be redesigned. They wanted, it was sort of a critical time element here, to get these parts designed and get into manufacturing. That night, that evening at home, I came up with a new arrangement for the controls of the hydraulics systems. The next morning, I gave the way I thought it ought to be, and they could go ahead then with getting the final design papers drawn up and get this into manufacturing.

Bernard's most memorable design experience for the cockpit layout he drew from his pilot experience even though he was a young engineer at the time who felt humble in the presence of senior design engineers who worked on some of the first commercial airplanes. It is memorable to him because his design was used later in spacecraft:

> I made the comment that this was going to be a short range airplane. There would be a lot of visual flying into airports. The pilots would really need a horizontal reference to fly the airplane, a reference to the horizon for level flight. To do this, the glare shield over the instrument panel could be made flat across the top as much as possible before it curves…the project pilot said to make a glare shield over the instrument panel in the mock up that we had of the cockpit and he would take a look at it… when he saw it, he thought it was a good idea and the design should be that way.

Later, Bernard's former boss participated at least tangentially in the design of a space shuttle. His former boss told Bernard that he recommended the flat glare shield idea. Even young engineers, as Joel in Category 4 points out, can have great ideas that older engineers need to learn to solicit:

> Because [the space shuttle] was basically a two man cockpit, "they came to us to go over the design of the [AIRCRAFT1] to see how they might incorporate some of the features of the [AIRCRAFT1] in the space shuttle… the space shuttle crew might like to have for a horizontal reference to fly the airplane and land it" …and that's the way they designed the space shuttle.

Bernard described a sense of uncertainty in design in only one of his experiences. He designed an external camera mount that would be used for a very short time as a one-off situation while he was employed at an airline (OES). He had only his calculations and no test data before the design was installed. Here, he followed a linear design process with no prototypes or bench tests where the actual use of his design was the one and only test. He did, however, have the airframe and powerplant integrator engineers review his design:

> There were speed restrictions on the airplane because of the tail camera that [company1] said we should not exceed… It was like a cold sweat flying to [location1] with the camera because of any unknowns on how the tail was going to react on the airplane… the first thing I did was look out the airplane when we landed to see that everything was still in the right place on the airplane. We did.

Edmund talked about a recent design experience that he thinks could have gone better if his management team had a different risk attitude. He was part of a multidisciplinary team looking at a particular system, where the designers belong to the propulsion group, the dynamicist studies vibration, and Edmund owns electronic monitoring systems that can detect vibration. Here, Edmund encountered epistemic uncertainty regarding whether the propulsion system would have unacceptable vibration or not. His response was to engage higher management in the decision process:

> The dynamicist was stating that he believes the drives need to have the option to be balanced and we should have the ability to measure the balance of them and to modify the balance of them on the aircraft and to at least measure the balance of them in case we have problems. That was his side but then the design side, the transmission side stated that they don't

> feel that it needs to be balanced. The vendor will balance them before they will deliver them. They will be fully balanced. There won't be an issue… I was stuck in the middle because I have the system that actually measures the balance of the drive shafts… I don't not trust the dynamicist guy but I worked with the designers more… We put together a risk. We talked about it. We had 2 different sides that were completely in disagreement with each other. We brought it to management.

Luciana had both senior design experience and internship experience but her transcript focused on her senior design experience primarily because the interview protocol questions focused on experiences of her making decisions. The most difficult part of the senior design experience was the *fly* portion, in which the pilot experience can be classified an epistemic uncertainty:

> The biggest problem was we had to fly it ourselves. None of us in my team had any experience with flying an RC aircraft… It crashed pretty much immediately and a lot of teams had the same problem but it was a little disappointing to not really get to see if our airplane really was able to do all of the things that we said it would do... We didn't know how our friend was going to be able to fly the airplane... I think that was the thing that I was most annoyed about in the whole thing… that was really frustrating. I felt that we were on an uneven playing field due to that.

Decisions on Luciana's team were emotionally driven even though there were more objective tools at their disposal, such as a decision matrix:

> We thought it looked better so we wanted it… It was we'd recognize that they all were fairly good and we just had to pick one… I felt like a lot of times it was out of frustration… I felt like we were making the decision matrix the way we wanted it to be… which one would be the right decision? A lot of times you just have to wait and see or like pick one and see how it feels… There was no way, with the knowledge that you had at the time of the decision, that you could have known any better.

There were design configuration and sizing epistemic uncertainties that Luciana encountered: "how would our battery last the longest. What was the least weight? What was simplest to build also is a big component." So she and her team conducted a few bench tests:

> Helping us decide what wheels we wanted. We would test a bunch of different wheels and see how long they took to stop in order to be able to calculate the takeoff distance …we tested a couple things out with how much power did our motor and propeller system really have… we were all a little concerned because our tests all came back fairly different… We tried it out a couple of times in terms of we would turn it on and drive it around the hallways in the basement but not fly. Sometimes we would turn it all the way up to capacity and hold it to see what sort of force we were expecting.

Miranda experienced simultaneous and interrelated epistemic uncertainties in cultural differences, data management, and schedule management in one of her first post-doctoral assignments in a research laboratory in a foreign country. She was trying to decide whether to include a baseline experiment or to use some form of previously measured data, and this was an agonizing decision for her:

> It's been a really big cultural difference for me learning how information flows… No one wants to give you information… lost information because of legal reasons …my primary responsibilities are designing the human in the loop experiments… I was trying to figure out whether we'd run a third [experiment]… Do we have a reference point? How are we actually going to say that our [design] is super useful if we don't have anything to compare against. … It was a really big deal though, because it also meant increasing the amount of work that we had to do. It also meant delaying some of the real actual work that we were on the hook for …first time I've dealt with a moderate level of responsibilities… I have regretted and rethought this decision 1,000 times, because this is the biggest one I've made so far on this project. It also shaped everything because it was made so early on.

In an event that Stephen in Category 4 describes as the "gotcha" moment, Miranda discovered a resolution to an epistemic uncertainty that she had not considered during the planning stages. She found out in the execution of her experiment that there was baseline data that she could have used:

> [Experiment participant] said ‘I don't understand why we need to have this discussion because there's a whole project already devoted to answering all these questions. You are effectively redoing all this work’… It was so tense in this meeting room because everyone was looking at each other, and then [experiment participant] looked at us and he said ‘do you know of [project3]’... My first reaction was I've never heard of this project… It never occurred to me to really look at all the other projects that had been done. I just put the information that was given to me from the project manager because I started on the project late.

Vincent has a few years of professional experience and has been assigned schedule and budget responsibilities in addition to technical cognizance responsibilities. He spoke of two incidents, one having a pressing schedule requirement and the other not as urgent.

For the urgent issue, Vincent faced two epistemic questions: “number one, can this part even be installed on the aircraft… second question being, how is going to affect the way other pieces interface with it.” His solution strategy was first “, rel[ying] on my expertise on that point and knowledge of how things are fitting together. With that particular component, I own the other pieces that are around that component.” Secondly, he “got with my designers and I said ‘CATIA support,’ and then I had them help me draw up a worst case installation… Also talked with a couple of manufacturing folks that actually do some of the installation on the floor. Those guys are a great resource… We were able to use that, put a case together, and present it to engineering management”.

4.3.2.2 Team Engagement

Plastic participants give the design their due diligence and then ask for informal peer review quickly. Sometimes, their due diligence includes checking their work through a checklist or process that someone else created or established. That someone may be within the company or team, or it may be a broader pool of knowledge from a professional society. This two-step process gives them more confidence to take their recommendations to higher management to make the final decision.

Bernard engaged his superiors and teammates to review his designs after he gave the design his best effort, but not before or during his design work. He mentioned generally his engagement with his superiors and teammates:

> You try to be as thorough and try to get other people's feelings on what you're doing and see if it is the right design… When you try it out, you see if it works or not… the main thing I think is important is to try to get as wide an outlook, as wide a view, with other people, get as much open view, of what's all involved, what other people are doing, how they're connected. Good communications… Be more thorough, you just learn, you never stop learning in most anything.

Diana earned an electrical engineering degree and went to work at an aerospace company, so she needed to learn the company's product line in addition to understanding the responsibilities of the job, which primarily includes defining requirements for contractors and then verifying the contractors' work. Her company abides by a clear decision process, including large meetings to prioritize problems to fix, and more discipline-specific checklists to verify fixes:

> I need to make sure that my change is not going to somehow mess up their whole system or their system design is not going to somehow negatively impact my change, so we do have a lot of checklists and a lot of procedures to review all the changes and make sure that we've focaled with the right people, and we also have a lot of meetings with the supplier.

Edmund's management team decided to take the "wait and see" route. The consequence of "wait and see" on performance and schedule was clear when they found unacceptable vibration later. The solution from the management team was to do something quickly and move on, and this annoyed Edmund:

> The risk was actually realized where they ended up having a really bad issue of unbalanced drive shafts on the aircraft. It delayed ground testing 2 months… It was not an optimal solution that we could pull together because we didn't have the amount of time to pull it together and do the usual design paperwork… We had to band aid something on to try to continue ground testing… we spent more money than we would've because it was emergency fashion instead of normal planned work.

Miranda considered several options for obtaining or creating the reference point data and summarized the data in a decision matrix, a tool that Edmund and Luciana chose not to use. In addition to leveraging her own knowledge of running experiments, the biggest decision making steps to populate the decision matrix were cycles of conversations and approvals from stakeholders:

> I talked to people in the group. I talked to my boss. I relied a lot on my own experience because I had done a similar validation study… big meetings with the head of the departments here and there, or all the big players, the bosses of everyone who had an investment in this project… Then we're going to try to clear this with the [government office 1], which they said they were okay with. Then we went ahead with it.

Much like Philip, Miranda wants to talk to her teammates as her uncertainty management strategy: "our lunch hours are a good hour long and we have breaks, there's a lot of exchange of ideas that happens and enriches all our research… Talk to other engineers who know the field." She noted that there are hindrances to having effective conversations "when you want to leave good impressions on people you are so stiff and unlikely to admit when you're wrong, or when you're not sure, of when you don't know." Much like Margaret, Miranda noted external influences can mitigate uncertainty:

> Conferences, or had to give these talks. I've had to take 2 or 3 steps back and try to express to someone who's never seen it, and it gives me a little bit more reassurance that the decisions that I made, or we made, were worthwhile…you make the decision and then you talk to a lot of really smart people about it. You get everyone's perspective, and at some point you have to make a decision. You have to have some conviction.

Like Miranda, Vincent has improved in his engagement of peers and engineering superiors to mitigate his uncertainty:

> I ran it through a peer review as well to make sure I wasn't losing my mind… I use a lot of peer review. I rely very heavily on my peer's inputs and opinions… the analysis was very well received because everybody was already in the loop, everybody knew it was going on already. Again, that goes back to reaching out to folks that know a lot more than you do… just having everybody in the loop, everybody knowing what's going on, and you're kind of presenting the analysis as you go, and everybody's giving their input and helping to make corrections… Doesn't mean that every suggestion is right or can be implemented, but at least you're not flying solo… You've got some backup, you've got people that are more experienced than you are by doing that for you.

Vincent continued to note the value of more experienced engineers, seeming to take their word at face value: "Getting coordination, coordination's key. Making sure you got the right people on the project is key… people that are far older, people have been in industry a lot longer, and you ask around. You ask your peers in your immediate group, you ask your supervisor, they'll point you to the right guys because they've worked with them before." He values the more experienced engineers' tacit knowledge: "I think a lot of it has to do with the history: has it been done before?"

4.3.2.3 Personal Response to Uncertainty

Plastic participants have gained some proficiency in asking for help and overcoming the hurdles of being unfamiliar with a subject or topic. Equipped with information from others, a Plastic participant has a subdued emotional response to uncertainty. There is comfort in following someone else, and it may even be confidence to finish a design project well.

For Diana, the second part of the design process is specific to her job. Following predefined processes is her management strategy for uncertainty; the completion of the checklist is the signal that her work is complete:

> We update our requirement documents and send it off to the supplier and the supplier will update the software based on those requirement changes, send it back to us, we test it, we make sure everything's good, catch any problems, make updates, test it again, and we're good to go… There's always some uncertainty, and it's really following the processes, getting a lot of input and support from other group members, and we've got all of these checklists to follow and so forth to try to limit any uncertainties.

For Edmund, his management strategies for uncertainty include leveraging his knowledge first, then following the program procedures of apprising superiors, and then consulting with Subject Matter Experts, but not formal design process management tools. What the lead engineer chooses is the path to follow:

> I think about my past experience, my knowledge of the systems, of the physics involved, not equation based but past experience, and your

> engineering intuition. Then you follow the procedures the program laid out… Give them a one slide quad chart presentation. If you put green on it they're happy, if you put red on it they're not happy… they said use ace or six sigma tools but we don't use any of that stuff. We just ... get a small group of knowledgeable people, not in a room but in a conversation, and brain storm together and have the lead pick what he wants to go forward with… We usually don't debate too much on various options because they cost more to debate than just to pick one and go forward.

Edmund prefers his individual work to get an approximate solution based on his prior knowledge and make progress, but he still leaves a little room for new ideas from other teammates:

> They just want us to make an 80% solution and not make sure it's going to 100% work. They just want to get us 80% solution with the cost of 80% or 40% and move on to the next thing. Then not have to make a science project out of it and just pick something and move on. … We don't want to sit here bickering about which way were going to do things… I've done this before, I know which way will get us complete on the project. Might not be the most efficient but I know it will work, but I will listen to what you have to say so please give me your opinion… You don't know what their opinion is unless you actually tell them what's going on so they can give you their opinion.

Luciana managed her uncertainty by relying on other teams' previously proven work and by relying on the approval of her superiors. Luciana even expressed confidence about her task:

> We didn't have a huge concern about it because the kits had been used for years. This project was something that had been done over and over again every senior year… I felt almost like no matter what decision we made it would be fine. That was pretty comforting. I knew that there wasn't one absolute killer decision… there were lots of solutions and that no matter what we did, we could optimize it… [Course professor] was extremely involved. He was at all of our design presentations and gave feedback. He was often down in the senior lab helping us design our aircraft and build them… Also just having our professor and our classmates all see what we were doing. It gave us the feeling like what we're doing makes sense… Everyone was able to ask questions and challenge you on your decisions. Sometimes from those presentations you make changes and things like that. I found that really effective.

Notably, Luciana mentioned the matter of gender as non-negligible. She was inspired to pursue engineering by a female science teacher in high school. But particularly in her senior design project: "it was the very first all female team at [university1] that had existed. What was interesting was that our professor was really excited about it… All of them had on their goal list to beat the girl team… Our professor got really upset with all the teams and he gave us this big ethical and gender speech in class." While this did not appear to have an effect in her team, it seemed to have an effect in other teams.

Miranda described her emotional process of making these decisions and executing on them, including confidence in a decision because of justifiable evidence: "Personally I felt really good about our going forward… It was very classic. I knew I could justify why we had certain results. … lot of times we really, really regretted this decision, because it felt like we were stagnating on something that wasn't even critical to our project… It's not fun because you are essentially redoing and emulating work."

Vincent is not afraid of uncertainty; rather it is a warning that the design is not complete: "I would say be aware of it and learn from it, but don't be scared of it because it's always going to be there. You're never going to get away from it, so stop trying to get away from it… Uncertainty is a good warning that maybe you don't have the right answer to the problem… you have not been able to convince yourself, then maybe there's still a problem."

4.3.2.4 Reflections on Learning to Manage Uncertainty

All the participants were asked to reflect on their growth in ability to manage uncertainty. Edmund thought his process has not changed. However, Diana continues to learn: "a lead, actually once a week or twice a week, would take all of the new hires and interns and just talk about airplanes. He'd just start teaching you about the system and held classes… I had started taking on more responsibilities and you start at square one again. It's like 'Okay, well, let's learn this system now'."

Now as Luciana has moved to other projects, she has reflected on her growth as a designer: "I notice a lot of iteration in my research… just taking the time and being patient is really important to move forward and to trust that you'll continue informing the problem as it goes on, which is something I like… Just being willing to know that your answer might change."

Much like Luciana, Miranda noted her growth in appreciating the complexity of a problem: "Obviously you can't control everything. Obviously you cannot control who is going to talk to you, who you're going to get information from… the process is iterative. There is definitely maturation when it comes to understanding the nature of a problem… Fully having an appreciation for the complexity of a problem comes in stages."

Vincent noted his growth as a designer in completing this design project:

> Give me a little bit of confidence having never really done it before… my transition to the [AIRCRAFT1] program, was a big one. That was a big confidence booster for me… For me it was getting thrown into the deep end there, and then just practicing executing on it… I relied a lot on my peers, and I think they're largely responsible for my growth as an engineer, for the success I had making that transition… The design process is the same, the decision process is the same. You're just executing some things a little bit faster… I would say that the majority of engineering problems are, you never reach certainty.

4.3.3 Category 3: Tolerant

Tolerant engineers have a good awareness that uncertainty is ever present and will never be eliminated in the physical parts and systems that they are designing, and there is another source of uncertainty as they engage customers and teammates more deeply in the design task. Tolerant engineers are trying to understand the goals and concerns of the other stakeholders, which may remain undeclared. Though they describe projects as team efforts generally, they simultaneously express a significant sense of ownership or investment in the design task. They are guided by foundational scientific principles, an expert behavior of deep conceptual understanding (M. T. H. Chi et al., 1981). That deep investment and deep understanding may be the signal to others that they are Subject Matter Experts.

Tolerant engineers use almost no emotions to describe themselves, other than taking an experimental attitude, which is to acknowledge that some solution paths may fail and that is better to know than not to know. However, they may use emotional terms to describe the components of a system interacting with other components, and viewing the component and the “owner” (another engineer) of the component as being happy when the components and their interaction satisfy all specified requirements.

The complexity of the design task requires careful planning and long term testing and experimentation in order to reduce epistemic uncertainty. Tolerant engineers are confident that there is an answer to the problem, whatever the problem may be. It will just be a matter of schedule and budget constraints on whether they will proceed to execute the tests to gain the knowledge. Tolerant engineers may describe uncertainty as risk, where the attitude is to manage risk rather than manage uncertainty; risk is frequently thought of by the indicator "critical to flight safety".

The participants whose transcripts compose this category are Abraham, Bertram, Jacques, Nathaniel, Oliver, and Viola. These participants are spread across research institutions, propulsion companies, and airframe and powerplant integrator companies. Abraham is the most experienced participant in this category, having 34 years' experience. Viola is the least experienced participant, having 4 years' experience.

4.3.3.1 Forms of Uncertainty

Participants in the Tolerant category have a deep conceptual understanding of scientific principles that govern the performance of the systems they are designing, and that knowledge equips them to explore epistemic uncertainties well. They are now aware of aleatory uncertainties in their respective subject matter areas. They have a broader view of their peers as teammates who share decision-making authority, and communication with peers concerning design introduces ambiguous forms of uncertainty.

Abraham's most recent design task is conceptual development of a new aircraft configuration. He describes his responsibility as an iterative converging design process to find a compromise solution among multiple systems that meets the key aerodynamic and manufacturing requirements. Some portions of the work are individual and other portions are collaborative:

> Individual engineering tasks or items to do myself, but also have the responsibility to consult with our various flight technology engineers to

> design and solve numerous problems… basically I'm allowed to observe all aspects of a design… so I can spread my experience around. to make sure that each designer is following the 4 basic rules or requirements to minimize: 1.) drag, 2.) weight, 3.) cost, 4.) schedule. I go around and check on every part to meet the requirement for that part as well as the top four items. It's a continuous iterative process to keep checking on all the designers until you find a compromise solution that works... Most engineers think you can cycle through this process once, but it's not true. You have to go through it about every six months because you're evolving the design and narrowing in your requirements.

While most of his work focuses on four basic rules, Abraham cannot ignore anything that is a flight safety risk. Part of his Subject Matter Expertise focused on fly-by-wire controls for the pilot. Silvia had classes on building in triple redundancy, and Abraham is actually using redundancy as part of mitigating risk of safety critical designs. Abraham has a clear process of identifying and prioritizing flight-safety critical items:

> If you're wrong on drag, it's not going to kill anybody. But flight controls, if you have a failure mode that you haven't thought of, don't know how to account for it, it could be a disaster. Those are the ones, that ambiguity, are really more important to catch them, there has to be no question as to how it's going to work… then it gets down to creating the failures and making sure you've covered all the possible paths. And then you categorize them, these are critical, these are not so critical, and these are

> benign. There are many failures that are in the nuisance category. If you have enough redundancy, it's okay. Then you come up with , after you solve the critical ones, make sure those that are life-threatening or aircraft-destroying but still nobody hurt, take care of those first… keep working the most critical ones first, and work your way down to the nuisance ones. Then flight test and you're ok.

Abraham describes his experience of uncertainty as an awareness of ever-present uncertainty and long-term management strategy. His strategy is to focus on the four big requirements, to spend some time doing textbook analysis, and then moving to small scale testing before full scale testing. His process follows government and military product development (National Aeronautics and Space Administration, 2011):

> Ambiguity is everywhere, and what you have to balance is how much, kind of back to the basic four, drag, weight, cost, schedule. You have to determine how much trade study or analysis is enough. Because you never get a 100% answer… Analysis has reached its end and the only way to reduce ambiguity further is to do some sort of small bench test… that gets you close enough to go forward with the design and then you would go to the small test (like wind tunnel) to remove further risk before you get to the final design decision… get further into the full aircraft simulation model, and run through scenarios in that. That part's pretty important, because you get a total aircraft simulation model, that has integration of all subsystems.

Bertram has nearly the same years of experience as Abraham, but with considerably more variation, first in running a family-owned manufacturing business and then moving into the customer support side of engineering and design. He views the engineering drawing as the final design authority, but that it is clearly a team effort: "engineering drawing or overhaul, there's always more than one signature at the bottom… You can look at drawings and who worked on the team that developed the part… no one person has all the answers. We have become so specialized. The breadth of what I work on is a lot and there's very few of us that do that."

The forms of uncertainty that Bertram encounters are more schedule-oriented for repair and overhaul responsibilities: "I think that's the biggest difference, that there's a little more uncertainty about what tomorrow's going to look like on the repair side." He gave an example of finding an unexpected failure and providing key in-service information to the design teams about that failure:

> If all of a sudden a gear has come apart and they don't know why, they will ground the fleet… As overhaul and repair, we might be going back and looking at those parts that have come in on an engine for repair, even if it's not in there for that part, we might get an order to pull those pieces, whatever they are, and do an analysis… they look for historical information if we have it… We keep a lot of data to mine. We will supply whatever they need… When you absolutely have to get something done, you'll find whatever resource you need in order to get your parts made or get them moving and find the resources.

Jacques' most recent experience included "redirecting the program and rebuilding the program… reconstruct the design of the whole research project program to find a way that we could use these [components] in a value-added research context so we can do some research that will be valuable with the [components] without scratching all the work that's been done on them." The goal of his effort was to "Improve communication along all lines, improve transparency" because "it's my job to make sure the sponsors get what they want" from a supplier with whom the sponsor had a "history of a pretty poor working relationship".

The uncertainty Jacques encountered most was epistemic, the volitional uncertainties of the supplier and the sponsor. His action to this was "collecting information, getting every party's point of view, understanding the stakeholders, understanding a little bit of the history of why things were the way they were. The first thing was fact- finding and information gathering, and the second part is to take action based on that information". He noted behaviors such as "People have their guard up and you're going to get a lot more opinions and negative comments." He noted several sources of uncertainty: "You're still dealing with people, personalities, attitudes, time constraint, budget, and there's someone supervising you. You have a customer."

Nathaniel's most recent assignment occurred because of sudden personnel changes that are expected in the aerospace business: "When he got laid off in one of the big layoffs that happened, they dragged me off of the project I was on to come replace him as the experienced technical oversight… At the time, there were about 5 people on the project. Now, we're coming really close to completion and we're down to three including me." Nathaniel was assigned technical cognizance responsibility where he saw multiple systems related to propulsion interacting, and he led the converging design process to a compromise solution:

> The challenge of moving it all over the place is that each system has an environment that it has to live in…creating an environment for all the different systems, electrical, hydraulic systems, fuel systems, pneumatic systems… Everytime we moved it to a new location, there may be components that had to move along with it that really didn't want to be what we were taking and having to rebalance all of those compromises just to try get a happy system and an efficient structure. That is the challenge that the designer is tasked with solving.

Nathaniel's design process included balancing trade-offs, where he describes encountering design uncertainty that Thunnissen (2003) defines as "variables over which the engineer or designer has direct control but has not yet decided upon. An example is the choice an engineer has in selecting a given component among a set of possible components. Design uncertainty is eliminated when a system is complete as all choices have been implemented":

> You typically start with ... I like to call them blobs. They're space holders… So I don't go model that starter in great detail. I'll model it as a cylinder that gives me a physical shape… We went through many iterations of exhaust configurations to produce the right amount of pumping to get the right kind of mass flow rates. We moved inlets around based on the shape of the contour… We struggled with at least 4 different

> iterations, major significant iterations of engine mount systems and actually wound up using an example of an old [aircraft2] to build what we termed a space frame, which is actually a pretty old concept… That came from a much older and more experienced design engineer that I've been pretty fortunate to work with several times in my career. He was there just for such an occurrence.

Oliver describes his flight test responsibilities as preparing and executing flight tests: "It's writing test plans, it's executing the flight tests, it's writing the reports, doing the post processing analysis…Working with the pilots…Have them use the charts and make sure that they're comfortable doing it before it gets out to the pilot community…Make sure that you meet the contract." He describes his goal as: "You're trying to flight test the aircraft. You're trying to make a good product that's reliable, repeatable, and safe of course." He is also balancing his superiors' expectations: "Program management is jumping on top of us to say whatever way is the shortest time and the lowest cost."

Oliver emphasizes that the goal of flight test is to obtain repeatable data to support the designers who will support the end-user pilots: "you need to repeat some of those points or open the envelope a little bit deeper and the other pilot can't repeat it, what's the sense in even trying it…you've got to think strongly about the repeatability…If you can't get that repeatable on a conservative level from all the pilots that have ever tried it and know how to fly emergency maneuvers, then you're doing it wrong."

Viola considers the design of aerospace curriculum as design. She faced a decision point of re-envisioning the whole course apart from other seasoned professors to stay with the incumbent routine that she felt was not meeting the need of the customer, in this case, the student:

> Do I go with the path of I should probably get along with my colleagues and just work with them and the way they're doing it?... or... Design the course I really want, which is very engineering design heavy? Introducing students to the problem solving process, very student driven, more my style… if I designed the course the way I wanted to it would look very different from the last five sections of the course, well the other two that the faculty was doing.

4.3.3.2 Team Engagement

Tolerant participants view themselves as an owner of a system, and they see their peers as owners of systems that interact with their systems, so communication and coordination are valuable for the success of the whole project. In this context, a system could be an engine or avionics, or it could be a process such as flight test or a learning environment; the key element is that the engineer has responsibility and authority for whatever happens. They view other engineers and their systems as one entity or the engineer as the spokesperson for the voiceless system, so to make the engineer happy is to have found a desirable solution to the design problem.

Abraham describes a sizeable list of stakeholders in the design process, with particular emphasis on his engineering team, which are his peers and his superiors. Marketing coworkers are expected to interface with the customer:

> Every IPT leader, every group involved in the design, as well as chief engineers, and/or folks like me, tech fellows, and/or staff engineers. There are regular meetings between different groups, to keep everybody collaborating… we're going out with different mockups at trade shows, CGI kind of stuff, trying to get the product reviewed by the customer before we make it. Our marketing folks see what the customer wants… The customer was pleased enough. The customer is invited to all of our meetings, even internal design decision meetings. They don't always participate, but, the invitation is always there… it's mainly up to us to meet our own requirements, to get a demonstrator out the door.

Bertram's response to uncertainty is reduce or eliminate uncertainty because of flight safety, but not as an individual: "there's a little more uncertainty about what tomorrow's going to look like on the repair side… we can't live with uncertainty in aerospace. We spend every hour of everyday trying to make that people are safe when they fly… If there is something that is uncertain, we need to make it certain, that we understand everything about it." In particular, he coaches younger engineers to get comfortable with the team environment, noting that being uncomfortable can lead to problems with career longevity: "hasn't spent any time working on the shop or working with mechanics, it can be very intimidating. We lose a lot of people because they're not comfortable and it is so challenging… And you're not going to be on your own. You're going to learn from everybody else."

Nathaniel's attitude about teammates is positive, where he seeks informal peer review as a check on himself and appreciates that engaging others may accelerate the convergence to a compromise solution:

> The difference, in my opinion, between an average designer and a good designer is the good designer knows who he needs to talk to to get what kind of information… A good seasoned eye will take at least one, maybe 2 iterations out of a design cycle... All opinions should be welcome because there is something to learn pretty much from everybody, even the people that are hard to work with…We've got another very experienced engineer who probably doesn't need my oversight technically, but I provide for him a sounding board, same as he does for me… I just need somebody to look at it and give me a sanity check.

Oliver relies on previous work documented after flight tests and others' experience in planning flight tests: "design these test plans, a lot of it is history based so what did we do before. Look at the reports, look at the test plans that were done before….History-based is one way but then talking to all the experienced people obviously… experience and the history. Those are my primary two things." For example, "The pilot will come in there and tell you if it's safe, if it's viable, if they could fly it."

Oliver iterates almost individually on his design of test plans, acknowledging trade-offs of schedule, cost, and volume of data, in preparation to present to the other stakeholders, especially his management, for their approval:

> PowerPoint slides, called the quad chart review process, but you come up with different options and you lay out the options. You try your best to not be biased when you're trying to make this… think about the positives and the negatives of doing each individual one… review that presentation material with the people that did have those ideas… That's what you want to convince yourself of when you do this exercise. You want to see are you making the right choices even though you might not believe that the other choices are the right choices you've still got to put them on the table … laid out in such a way that the tradeoffs are very well expressed…I'll go though that process a couple times until I feel that it's at a point where I could present it in front of a large group of people. At that point we will try to conduct a meeting with everybody that's involved.

Oliver experiences phenomenological uncertainty in flight test because his team is testing new configurations, new software, and new maneuvers. So he and his team have to be prepared for surprises:

> If it's a new helicopter design … we're going to get different results and we've got to be totally open minded about that …we tread on a lot of new turf… developmental testing. We find out surprises… in the performance group you don't see too many surprises…Structures, propulsions, they're

> going to see other things that are very characteristic to each individual aircraft.

Oliver's toolkit for measuring the uncertainty includes documentation review and consulting with other Subject Matter Experts. Troubleshooting of data collection instrumentation is another popular option, including consulting with SMEs specific to that instrumentation. As well, he thinks about the newly recorded flight data in comparison to the textbook analytical data he already has:

> Try to research it… we go back to the subject matter experts… I've had to dig into old data to see if on other aircraft… We tend to hunt after the instrumentation systems first … At first we thought maybe the instrumentation something got knocked and maybe we need to recheck the calibrations… getting the engine rep out to [city6] to do some inspections… then that's the revealing point of, OK, we've learned something new… we document this well… instead of looking at the instrumentation first, we might go re-brief, make sure that we're safe, and do a mid-point… something that threw the trending off a little bit and let's just repeat the point… that you didn't screw up a formula. If you're still uncertain you repeat the point as long as it was safe.

Viola's design process included a significant amount of data collection from stakeholders and then to try a few prototypes, both are human-centered design tools (IDEO, 2009; Maguire, 2001; Zoltowski, Oakes, & Cardella, 2010):

> I typically talk to other people. So I try to get feedback from lots of different individuals… got feedback from my boss, I got feedback from my fiancé, I mentioned it to him. I got feedback from a colleague of mine… I did some very, very, very little rapid prototyping. I'm using the word very loosely, of what would the course look like… I attended meetings with the other faculty to see how they were thinking about designing the course. So I tried to understand that design alternative as well… I actually emailed all of my students from when I taught the course in the spring of 2014… I got responses from actually about 12 to 15 people out of a forty-seven student class giving me feedback.

The implementation of her idea has some areas of behavioral and schedule uncertainty from the users, and Viola viewed these uncertainties as risk. Another element of risk was not getting feedback from the user about the design meeting expectations:

> I had no control over the topics that the students were doing for this project. This is the most risky part of my design… I was a little nervous because it was hard to predict. I didn't know how long these things would take… making sure my users understand that they should tell me if things aren't going well. That's been really hard with this group. To get them to complain unless I push a lot… knowing that I'm not going to get all the information that I need even if I ask for it in class and needing to find other ways of gathering that information… you're working with a user group that has a life outside your class.

Like Oliver, Viola encourages questions: “I know many many people who don't ask for advice. They just don't ask questions. Who don't talk to people when they're stuck and they just get in a worse and worse place.” Like Abraham, Viola notes a particular view of uncertainty: “Uncertainty is less of a fear as much as a problem.”

4.3.3.3 Personal Response to Uncertainty

The Tolerant participants have an almost neutral emotional response to uncertainties they encounter, because they are comfortable with the notion that some ideas or paths will be productive and some will not. They are confident that an answer exists to the design problem, and that it will take resources and iterations to find it. This is in marked contrast to a Brittle participant’s low confidence that a task could be executed at all.

Abraham described his personal response to encountering uncertainty as a welcome challenge to be addressed as a team:

> Have patience. There is ambiguity and uncertainty at all levels… Ambiguity should be something to look forward to… something not be feared, but it's a challenge to go figure it out. try to be clever enough to solve that uncertainty …an answer that's either 80% good, or design a trade study that you can deal with that ambiguity in a manner that won't take forever… you should never think of it as something you have to solve yourself… Collaboration is being encouraged more these days.

Jacques' personal response to encountering uncertainty is much like Abraham's, a welcome challenge: "I took it as a challenge and opportunity… Get everyone's perspective and to really be patient and make sure I understand things very well before I took any action… maybe that's the way you manage risk: you take the middle ground." Primarily in this design situation, "Understand the risks, not only to you but to the stakeholders and to the other entities that are involved in any decision. Also, timing. I think there's a time for action and there's a time for fact finding and information gathering." He re-emphasized patience while converging on a solution like Abraham did:

> Understand or quantify risks. Understand what the risk of a certain outcome would be. Understand the possible outcomes. Understand the risks associated with those outcomes. Make sure that you have a good understanding of the situation before you take any action because sometimes it can be harder to undo a wrong action. You have to be patient and wait for the right time to take action. Believe in yourself and have confidence in yourself. Know also that it's okay for things to go wrong.

Nathaniel's overall summary of his job is: "I'd say uncertainty to me is anything below about 95% sure. I spend most of my time dealing with a tremendous amount of uncertainty… not certain that it's going to function appropriately. We mitigate the uncertainty with experience, interactions with other groups, to help us make design decisions."

Nathaniel's personal approach to managing uncertainty includes a "good air of humility", like Jacques and Abraham mentioned about patience:

> It helps me when I come into a project early enough in the design process that I can grow and learn the particular peculiarities of the design… The most important difference between me and a new hire is I'm experienced in dealing with problems that I have created on my own. At this point in my career, I'm not so proud or so sure of myself that I'm right, that I have balanced all of the compromises appropriately, or that I even am aware of all of the compromises, all of the requirements that I have to actually meet. I'm very active at seeking out the people that I do know I need to be working with.

Oliver's personal response to uncertainty includes comparing new data to some baseline, expecting data to look like the baseline, but not ignoring the data if it does not follow the baseline:

> Every other helicopter that [company3] had has been pretty much the same design when you think about it. It's one rotor blade system with a tail rotor blade. We kind of know what to expect for the most part… performance testing, you go by a lot of trending… Don't ever, ever assume that things were supposed to happen the way that they have in the past… make sure that you always expect the unexpected… Try to have a plan if deviations come up.

Viola's personal approach to uncertainty is experimental: "I treat them very carefully. I don't take things personally which I think is very difficult as an instructor…

my attitude had been more experimental… I'm testing it in the classroom… I check in with them a lot… We're prototyping constantly as an instructor." She noted an adherence to foundational principles as a mitigation of uncertainty:" with the uncertainty is really sticking with what you know … underlying principles are still working for them… I'm going to stick with what I know works. Those underlying principles and then test little incremental things as opposed to large scale changes."

4.3.3.4 Reflections on Learning to Manage Uncertainty

Tolerant participants look back on their supposed failures as teachable moments. They have had enough time to find that they can recover from those failures and that the next time they will be more thorough now that they have expanded their awareness of sources of uncertainty.

Nathaniel noted his own growth in managing his emotions towards design projects: "you feel very overconfident and you come out of school… lacking the fundamental understanding that the complexity of what you're about to do and the number of compromises that you're going to have." Like Miranda, Nathaniel mentioned "compromises that are made early in a project can haunt later aspects of a project." Like Ross, Nathaniel mentioned "to start taking apart into its simplest pieces, to start dealing with those pieces as they pertain to the requirements, and to begin balancing those compromises."

Oliver noted his personal growth as a designer, including learning from failure, breaking problems into smaller pieces, and managing his own feelings toward failure:

> My senior design project was totally something that we've never tried before… you had to pick apart your problems, know how to attack them, figure out the options of the paths to go, what the best choices were, and make sure that everybody is in agreement … It was disappointing. We did fail. We learned a lot... you can't look at anything in engineering as ever a total failure…So ask the right questions, because without experience you can't ask the right questions all the time. Getting rid of the fear of not asking the right questions I think is the important key here.

Viola notes her growth in accepting that there might be failures and those can be learning experiences. She also notes getting her emotions under control as she works through successes and failures:

> You think you know what you're doing and oh no you don't… I'm going to just try and we're just going to see what happens and it's going to be okay if it doesn't work out, and so with the uncertainty part you're saying it is totally uncertain because you haven't had the experience yet… definitely being more flexible and not taking things personally, because I think there is so much uncertainty in where their projects are going to go, what their interests are, how busy their going to get… not taking things personally which was very hard after last semester and as I mentioned, standing my ground.

4.3.4 Category 4: Robust

Robust engineers anticipate the unexpected, which makes them willing to try new methods, new processes, and new solutions. Novelty requires real data instead of opinion to verify and validate decision paths. Because of the complexity of the design tasks, they must have significant engagement with their teammates and other stakeholders. Team engagement, because of the demand of actionable data, may become confrontational.

Epistemic uncertainty is the uncertainty that can be reduced when their teammates produce actionable data within their subject expertise. Aleatory uncertainty (irreducible uncertainty) is now a fact of life because the goals of the complex design tasks they are working on may include dealing with the fact that no two people do the same thing the same way, whether a manufacturing task or a pilot task. Additionally, because of confrontational team dynamics and because of engagement with customers, partners, and suppliers, the ambiguity of volumes of verbal communication is introduced (Daft & Lengel, 1986; Eppler et al., 2008; Philippo, Heijstek, Chaudron, Kruiswijk, & Berry, 2013). Even if a requirement is written and agreed upon, it is still open to interpretation.

Robust engineers hint at strong emotions tied to the apparent success or failure of a large design project, but they also describe their confidence and their willingness to persevere even though there is a high risk to completion. It is in this category that engineers may use the word "intuition" as they create new methods, processes, and solutions, an intuition that is supported by years of experience in completing similar projects. They also amass large enough teams that they must manage others' emotions and uncertainties in addition to their own, because they are carrying large decision responsibility.

The participants whose transcripts compose this category are Curtis, Frank, Joel, Ronald, and Stephen. It is this category of participants that have handled their complex design tasks well outwardly and have some inward struggle. The robustness manifests in handling the stress of the task well, accomplishing the goals they set out to achieve. Part of the credit for handling complex design tasks well is following some prescribed process for which the participants received formal training or have a reference text, such as Six Sigma, Systems Engineering, or test pilot training.

4.3.4.1 Forms of Uncertainty

The participants whose experiences categorized the Robust group identified epistemic, aleatory, and ambiguity uncertainties. They mostly described design projects where they were exploring phenomenological uncertainties (pushing the boundary of the state of the art, trying something for the first time), which are mostly high-risk endeavors that need a lot of data to confirm that the new ideas are safe and useful. To do this well, the Robust participants need many teammates with their respective specialties to examine the new data, and that introduces ambiguous uncertainties as they communicate their findings and their opinions.

Curtis very much defines his role as a test pilot, a surrogate end operator. Flight safety is the driving reason he participates in design. He had several design tasks that he called efficient and straightforward, such as inserting previously proven attitude indicators from one aircraft into another. He also participated in more complex design tasks, such as designing threat displays, which involves human interface or how a pilot interprets data, and how to classify and prioritize detected threats. He said:

> What we did know, what are the general capabilities of what those sensors could determine about a threat, and what information about the threat they could display to the pilot…But what we didn't know was how the threats were going to be encountered in theater, so then that makes the prioritization a little more difficult task. How many threats do you want to display at one time?

In a different design project, Curtis and his team found a new phenomenon during flight test where they should not have "poke[d] that monkey in the eye again":

> We were testing the wind condition, we were coming in to land, then it happened to be next to the superstructure of the ship. We didn't know what's going to happen, that's why we were testing it…The more he stayed up there, the more difficult it was for him to land, until finally, he got into this big pilot-induced oscillation and just waved off…and not wanting to have his manlihood questioned, he came right back and landed in the same, exact spot before the engineers could tell him, "Don't do it," or right before anyone could kind of figure out what just happened. In retrospect, probably wasn't the smartest thing to do, as I talked too about build up and understand the next point and all that, but - added to the mystery - because then he came back and landed perfectly.

As a materials process engineer, Frank has steadily improved his technical cognizance. He designs and delivers materials to aerospace customers with particular requirements. Frank has consistently demonstrated his design abilities and his job now requires him to exercise these skills even more: "a process engineer. It's more for seasoned engineers, advancing engineers, who are more keen towards problem solving and long term problem resolution. That's kind of where I'm at right now."

Frank had a particular design task where he was uncertain of the customer's design requirements at first, which researchers have shown to be troublesome for design and implementation (Philippo et al., 2013) : "They wanted different properties within the same material… we needed to go back and ask the customer 'is this what you really want?' that really drove the decision to push forward with our process evolution… It was more about how do you design a fixture or a process around the material. It was more driven around material requirements and customer requirements versus our existing process how we manufacture a material. It's kind of a game-changer."

Joel as a director-level test pilot had engineering responsibilities: "technical conscience totally on my shoulders… my name goes on the flight clearance, so the technical conscience resides with me. I've got to make sure that we have done our due diligence." Here, he switched from singular voice to plural voice to indicate his team. He described his job as: "leading very smart people" and "it turned very personal for us" because of the conflict between engineer and pilot having different interpretations of the same phenomena:

> No pilot's going to love an engineer… There's always pushbacks, because there's some capability [engineers] want to take away from [pilots] that

> they know better, whether it's pride or whether it's just because they see from a different perspective. [Pilots] know Bernoulli, because they interact with them every day. [Engineers are] just plotting them out on a chart.

Ronald worked in a small company with a specific culture of taking risky projects to demonstrator prototype phase. Ronald described it as: "the company has a reputation for doing a lot innovative thought… So there's not a lot of entrenched knowledge that people have. It was strongly encouraged to investigate new ideas and different ways of doing things." To that end, Ronald said of the company, like Luciana, Abraham and Nathaniel desiring to stay with a project start to finish: "Engineers in that particular company were strongly encouraged to take a given area of a project all the way from conceptual through planning through detailed design and then some manufacturing engineering." The company attitude was still grounded in production reality: "we, working the engineering field, were very strongly encouraged to spend a third to half of our hours on the floor, working with the techs… If you couldn't build the product, you weren't allowed to release the drawing." This company culture probably accelerated the growth of his attitude toward uncertainty compared to his peers in other companies.

Partly driven by his uncertainty about his qualifications to get an engineering job, Ronald took the initiative to study beyond an engineering degree to earn a pilot's license and an A&P license to be an aircraft maintenance technician. He followed a conceptual to detailed design process as he designed a control cable out of a new material. He said:

> I was responsible for conceptual and detailed flight control design of this particular part… Initially it was me by myself. Several months into it they

> decided that the scope had gotten too large… worked with a few design engineers familiar with that area… hand calculation analysis for thermal expansion…handbooks and FAA advisory circulars… existing guidance, rough sizing for characteristics like handling qualities… Not analysis specifically, we went to testing. We did do physical testing. We built samples of the cables.

In particular, Ronald leveraged his A&P knowledge efficiently: "FAR part 23 and 25 laid out maximum pilot effort. So you design for what an average human pilot is able to exert on the control input. You assume that that is the highest load that the system will see." Then he applied the company ground rule of getting to manufacturing: "we had tried a few different manufacturing methods and had come up with a way of building and assembling these, and testing them that made us comfortable that we could manufacture in a reasonably cost effective manner."

Ronald, like Oliver, had baseline expectations about the performance of the control cables out of traditional materials but had an eye out for different sources of uncertainty:

> Steel cables have been in existence for so long that everyone knows how to check for damage… Carbon tends to be more unknown and more intolerant of minor damage, in that a small amount of damage doesn't necessarily progress at a predictable slow rate to failure… is this going to be a system very intolerant of maintenance work, very intolerant of other damage?

Stephen has held a variety of engineering responsibilities, some less exciting than others. In some roles, he described himself as a designer and in other flight test director roles, he described himself as an editor. The flight test role required due diligence much like Joel described: "Pretty high stress job. You have to do lots of simulations and be fully prepared for any emergency… Lots of room for risk and because you're going supersonic, you've got to fly pretty far from where you could land, so there's lots of danger there."

4.3.4.2 Team Engagement

Participants in the Robust category need many teammates to help them make sense of their design tasks as they gather new information. However, it can be uncomfortable to confrontational when teammates offer opinions instead of analysis. Robust engineers have demonstrated success in managing uncertainties from systems, and are now taking on larger responsibilities that involve people more deeply so that they can move collectively to a secure stance to make a good decision.

Curtis described the design process he followed, with significant emphasis on early involvement of the user: "I did some research… access to battle damage reports… design team had to make some decisions on how to display [threats]… We have operators involved in the design… scribbling things on the wall, we had operators involved in the design, and resource managers." He advocated prototyping early for all the stakeholders to see:

> Through modeling and simulation, in [company2]'s [simulator], we're able to actually utilize those in an operational scenario, and I have to say that is hugely important in making design decisions, getting whatever your decision is to as close to operational representative as possible….might be cartoons on the wall…you can get some really good animation in a PowerPoint slide now… the point is prototype early and often-- there's no prototype that's too primitive.

Curtis, again referring to ideas that have been proven, along with his team, converged upon a layout of the display: "So we separated the threats into immediate action required and not immediate, more advisory nature…Those are similar to how the aircraft emergencies are categorized, and we wanted to remain consistent with those." There were some decisions that felt arbitrary, such as how many threats to show to the pilot in command: "everybody in the room including the operator and the design engineer said, 'Okay, three.'" He noted the complexity of designing a display as an ambiguity, particularly a visual one (Eppler et al., 2008): "where a human is involved, that adds a lot of complexity to the design. Like five pilots, six opinions, especially when interpretation of displays is involved."

Curtis summarized the design process as the management strategy for uncertainty, using the plural voice exclusively, because Robust engineers need their teammates to create and interact with prototypes and simulations:

> That's how we handled that unknown, and I would say that that was-- we made it as little-- we eliminate as much of the unknown as possible -

> researched, brought the user in who was kind of the expert, and then-- but at some point we had to make a decision. There again, this is where the PowerPoint slide came in. We did have some real prototypes on a PowerPoint slide… They set threats up in the simulator; we'd fly through them and we'd go and look at them… this incremental approach. When the design was young, we had options. Then as the design matured, we'd narrow those options.

However, as Robust engineers may experience some confrontation, Curtis described reactions to design changes by the operators, whom he feels he represents: “But then it gets out to the operators and they don't see the agony, they don't see the whole decision making process. And they just see a warning… they have some unknowns and they started putting their own safety factors on their operations, not fully understanding that that's not their job.” Another change: “pilots were freaking out a little bit when they could sense their controls moving. That was kind of an assumption that we thought a little big of ourselves as, ‘Oh, I'm a test pilot. I'm so smooth, I can detect it but they won't know,’ and move on. There is nothing special about us.”

Even with intuition working for him, Frank still follows a prescribed design process of simultaneous exploration of possibilities, where he deployed several of his teammates to gather data:

> Six Sigma Black Belt. We have a "toolbox", a set of tools that we use. One of those is a thought-map process. We go explore all the different

> opportunities and options that you have… you look at the pros and cons, and the variables that you have that are controlled and uncontrolled… it's more an evolution in the [company1] methodology, like the thought map process where it's more an exploration phase. We may go down a path that leads to a dead end, for example, but at least you learn something… you get to a path that gives you some promise, then you start setting up scenarios, different outcomes … it's more about the broader scope and once you get the thought mapping done, and then drive down into specifics through process mapping and [Design of Experiments]… I had to manage different trial work, different paths, if you will, trying to figure out what made sense. So I was more the wheel on the hub and we had all these different spokes going out that you get information from the outer spokes… six or seven people. they had different projects, mini projects… those types of six or seven different areas we worked, it kind of gave us a direction of 'the process has to be change' to give us better material.

Frank further reflected on the indispensable need for his teammates as owners of resources necessary to solve a problem:

> It's a matter of making relationships and communicating with others in trying to avoid reinventing the wheel…It goes into a spiral where you can ask them why and get to the root cause, they're going to help resolve that issue…who is the person who can help me with resources…it's a matter of

> going to the people who actually control those factions and getting those resources secured.

Frank now manages other stakeholders' uncertainty as part of his job by producing reliable data to prove a concept:

> We're an industry that thrives on standardization, that thrives on consistency, and anytime you throw a change in that process, it meets with resistance right away. It was more about me as the manager of the project trying to sell this solution to others that would buy into it once I proved success…Our customers generally require a regimented program in order for us to produce material for them under contract…we have to build between 3 and 5 lots of materials, which goes through the full regiment of testing…we have to build between 3 and 5 lots of materials, which goes through the full regiment of testing.

Because of the deep personal investment in decisions, Joel demands tangible evidence: "you have to put yourself on trial… There's got to be some breadcrumbs trails. There's always that 'go test it'… I'm always scared of intuition… tell me the history… developmental tests community is really good at is documenting stuff… then operational test… deficiency reports… facts should back it up."

One of the problems Joel notes is the loss of facts among teammates as a design matures even though they follow a well-defined design process, where "seams" between phases are the culprits:

> If I'm moving from systems readiness review or a developmental to operational test to production or to in-service, each time there's a seam for that transition, I can guarantee you the people that are in position are the wrong people… there's collateral damage there, because so much tacit knowledge left with them, and that stuff you just can't get from a report.

In response to this, Joel took on responsibility to gain defensible knowledge: "joint discrepancy reporting system… so I was a big fan of that, because I could read all this stuff… this really established my technical credibility… I think from a discipline standpoint, is that people get away with how long they've been on a program or what their credentials are and they never have to reference a fact or a report." There were consequences to his confrontation of other Subject Matter Experts: "They hated me, and sometimes, people went silent on me. You have stuff like that."

As Joel's team attempted to solve the unpredicted failure mode of a flight-critical component, his team suggested a short term solution to buy time to find the root cause. The inspectors implemented a frequent visual inspection, which inherently has high variation (aleatory uncertainty). Joel called in a particular Subject Matter Expert, "They're specific engineers, and when you're going from failure management strategy, you have to have reliability engineering there… the unsung hero of all of this." He noted the team dynamic: "nobody double checks his information. That's the value of me sitting there going, I haven't done anything in three days. Let me go check this out. I think there's not enough teammates that actually help do that." Here, Joel demonstrated that he is as much a teammate as a boss, even though his double-check of the work could be construed as another confrontation.

In a second design experience, Joel found teammates' behaviors hindered progress of integrating aircraft with aircraft carriers:

> I have competing egos… I am always conscious of guys that know too much, the ones that are over confident in their position before we've assembled all the facts and put the body of evidence out there… guys that are taking a look at it from a shipboard compatibility standpoint. Multidisciplinary, multi-background, but we have to get on our ship within two days… even though it's the same class of ship. Each one was different… they now think it was missing was the thermo-analysis piece.

As Joel once took responsibility to gain defensible knowledge, in this shipboard compatibility test, Joel took charge to find the right SME, who was rejected by the rest of the team:

> He's like the head thermo-dynamicist for [COMPANY8] and he didn't charge any money for it or anything… [he] offered some suggestions… It really mitigated the effects that were happening out there… some of this ego stuff getting in the way and no one accepted… they just were very resistant into incorporating his opinion... most of these engineering events are huge emotional events.

Joel handles so much information from so many teammates that he has to have a sense-making strategy of a concise narrative:

> You're not going to veto the guy who's done the most homework or make some more sense. You're probably going to veto the guy who's the most emotional or the guy that wants to give you the doctoral dissertation on [failure mode]. You want to veto those guys, but the one that comes in and says, 'That's a story I can wrap my head around.'

In a second design experience, Ronald encountered epistemic, aleatory, and behavior uncertainties when he and his team were tasked with deciding whether and how to repair an expensive part that was dropped accidentally. He said:

> We really don't know anything about how it was damaged, the manner it was damaged, where it was damaged. That was a case of uncertainty just showing up unanticipated… coordinating the diagnostics to figure out the extent of the damage that was in place, coordinating with our own company and the other company their repair methodology that they accept… coordinating the diagnostics to figure out the extent of the damage that was in place, coordinating with our own company and the other company their repair methodology that they accept.

Ronald's team temporarily integrated with the customer's team to solve this problem, and there was initial skepticism on the part of the customer:

> The company we were working for actually had assigned about 6 engineers and a dozen or so shop technicians that were temporarily located at our company…the customer was more familiar with higher level manufacturing production, and we were more familiar with the materials we were working with… Within our own company on my previous program, we generally got overwhelming support for trying a new idea. Working with the customer's engineers, there was more skepticism on their part that we could accomplish what we said we could…from a larger company, a more conservative mindset, not really as willing to try new things.

Ronald and his team worked through the problem thoroughly by leveraging each company's strengths in the design process where it made the most sense:

> Not an unusual repair, it was more no one had ever talked about trying to do it on a 1 foot by 12 foot disbond area. We were relatively confident that we could map out the extent of the damage and make sure that we got that area that was cracked glued back together. The customer was not as confident that would solve the problem. If that repair didn't work, there'd be no way to know… we did some subscale testing, the test article verified that we could use pressure to force in lots of small places far away from where we were injecting it. We did testing and we were able to document to the customer… use their x-ray and ultrasound to verify that our repair was complete.

Stephen noted where the difficulty is in his job, not the technical side but convincing others of the quality of the work: “hardest part of a lot of engineering is actually not doing the work, but communicating your effort and why you made your decisions and why it's the best approach.” Communication is continual and confrontational through the design process like Joel:

> You do have to keep close meetings with all the parties that are affected. It's not just what you want. You've got to make sure, because you have to a give and take…sometimes the first answer they'll say is no, it can't be done. Then you need to say prove it to me…I believe you, but you sometimes have to be a little bit confrontational…so you've got to talk with a lot of people. You have to go up to them and let them know that they know more about their topic than you'd know about their topic…have meetings often. Show your progress to somebody. For one thing it keeps you on track, it forces you to be good about what you're doing and it also, maybe somebody didn't speak up in the first however many meetings and now they want to give you something…There's going to be push back in the beginning. There always is, so in the first few meetings as I was saying what I did, there was a whole lot of smirks and giggles and that kind of thing in the room…You may be mad at that person, but hey, they just helped you do the solution correctly or as correct as possible.

4.3.4.3 Personal Response to Uncertainty

Curtis' personal approach to managing uncertainty is to redefine uncertainty as risk in order to create measurands: "uncertainty is binary, you either know or you don't know… Risk, you can manage… what changing uncertainty to risk does is allows you to measure it… Measure it and manage it and budget for it." Here, Curtis also describes technical risk as influencing cost and schedule risks, and he is responsible for all three.

Curtis described his test pilot training as the key procedure for mitigating risk of phenomenological uncertainty, starting from a known point and methodically stepping towards the unknown:

> It's called build up and they pound this into your head at test pilot school. You don't go straight to the cliff. You incrementally approach an unknown. You start from an area of known, and then you slowly work your way into the unknown… even if things are going perfectly, stop, watch the trend, try to predict where the trend is taking you, look for things that you're not looking for.

Frank has deployed his intuition on recent design tasks: "I've run across several times where I add more heat, I will speed up the process, for example, based off of internal instinct from my previous experiences." For this most recent design, Frank exercised his intuition to reduce the design time: "My decision was to change the process to fit the material. And that was what drove everything. My gut feel was not to try different parameters in the producing process that would not work out."

Like Oliver, Frank looks for repeatability of a phenomenon to confirm that it is real: “like the experiment you set up that then reveals two factors that you never thought would be important, but they are…The proof is really in what the data is telling you that drives you in a direction that you want to go…they go through repeatability trials just to confirm what we've learned the first time wasn't a fluke.”

Joel noted his uncertainty management strategy of applying a conservative factor: “data points are hard and expensive to come by, and there was a lot more uncertainty with that and I think that your level of conservatism goes up with the level of uncertainty… you don't need to do that, look, yeah, 50%, and at some point it is cultural… they've been living the culture forever and they're okay with it.” Because uncertainty can never be eliminated, he added: “You just live with uncertainty… there's informed risk and you need to be comfortable taking risks… we talk about failure management strategy, but it is really about risk management… both consequence and occurrence.” He noted others’ learning to manage uncertainty: “what I sense from people is that they would rather rely on somebody else's experience."

Joel also has the same strategy as younger engineers for breaking problems into smaller pieces: “Before it had been a bundled risk and so what we did and so what we did is we dissected different parameters so they could run the risk model on only those separate parameters… I didn't know that you could reduce the risk by breaking it down into smaller ones.”

Ronald’s personal management strategy for uncertainty is to explore possibilities and to base decisions on real data, like Joel advocated. Those possibilities come from other teammates, and Ronald brings a technician perspective that other participants do not mention:

> Always good to hear everyone's input. Some different ideas, different perspectives… add more options that you can easily come up with, evaluating each on their own merits, testing whatever is feasible to verify areas where uncertainty is… exhausting all the different possibilities and doing whatever testing is available to you, talk yourself into it… generated data is something you do you yourself or tie in research that other people have tried or you reach out to other organizations or companies that may have done testing in a similar way…A lot of things have been tried before by someone, and you can find it somewhere… design manuals… approved structural repair manuals… The FAA's own documents, they have advisory circulars, the FARs, you have design, testing, and repair manuals in A&P. we relied on those a lot… It’s been tested, it's been approved, and we’re very comfortable that if you do the repair the way it's been prescribed, you're going to meet or exceed the original strength of the product.

Ronald has a thorough approach to managing uncertainty, exploring depth and breadth in a prescribed incremental build up flight test process:

> Flight test itself is a very well regimented step in increasing capability, checking it in flight. Uncertainty is dealt with by procedural process of their rigorous testing, from benign conditions to severe…uncertainty itself makes you more likely to checking more things, makes you test more and inspect more… The uncertainty makes you more likely to make the load cyclical, hundreds of thousands of times, repetitive, cyclic… it could be prone to cracking and failing and corrosion. So I think that uncertainty drives you to do a lot more of and varied test than you would do if you're using traditional solution. Presumably, someone 10 or 50 years ago has done that testing for you. The long track record gives you that, if removes the uncertainty just by it's been in service for so long and people assume it's able to do the job…you start thinking about all the other possible variables it could have and should address. It makes you think about additional testing that you want to do to try to eliminate unknowns. It pushes you towards more testing before production.

Stephen takes spends considerable time triangulating the truth with biased sources of data to create or understand a baseline, just like Miranda's experiments needed a baseline, but Stephen doubts his results:

> You start with the back of the envelope so I went to the textbooks… so you might start with asking around… you calculate the numbers that you have on the baseline of the aircraft. Something that you know. You start with something that you know and you build… You need a baseline…

> how do you know that your work is right? You don't know. The only way to know is to test it against things that you do know…I started with these textbook designs. Got what we thought were the results for other versions of the [aircraft1], which is only one. I looked at that. I looked at what the [simulation1] model of that gave me and I looked at what the wind tunnel test of that gave me.

Stephen’s personal approach to managing uncertainty is to confront his emotional response and move on to obtaining a team consensus:

> Uncertainty is really frustrating. It's one of those things that can really bother a designer… Now you question everything. Now you wonder what is truth… there's error in everything. Uncertainty runs and there will always be uncertainty so you just try to mitigate it… if you look at as many different aspects of your design as possible, you can get confident in that and then you get that uncertainty level to a small enough number and you show that number to people. You let everyone know and then you design the safety factor into that. Then you've got to run it by everyone again and make sure everyone is happy with what they need out of your design.

4.3.4.4 Reflections on Learning to Manage Uncertainty

Curtis specifically self-educated by reading *The Goal* (Goldratt, 1992) and using the concept of Theory of Constraints for budget and schedule management as they relate to test and development risk. He said: "Plan well inside the buffer, and then things will come up unexpected-- the unknowns, that's how you account for the unknowns. That's your buffer." He also said:

> If you set a target - and especially in challenging, complex systems - it always moves right, it never moves left because people kind of work to the target but don't try to exceed it… let's back up until we find where the known is, and then draw a path from the known to the unknown and figure out how you're going to get there… in flight tests, there's pretty severe consequences to walking off the end of the cliff, so you take a very deliberate approach.

Frank reflected on his growth of ability to manage uncertainty and, like Abraham, welcomed a challenge: "Don't look at uncertainty as a bad thing; it's an opportunity to go exploring more into why is it uncertain… The mystery and going digging and doing some research, the answer is going to be there." Now, he has internalized his thought process to the expert level where he does not express it verbally (Ericsson, 2006; Hoffman, 1992), which he calls intuition: "it's really driven based on Six Sigma principles is what I do, that I've learned to expect the unexpected. That's always there. But the more I do this, the more I get instinct, or mother's intuition."

Joel had several suggestions for learning to anticipate uncertainty, primarily to follow a prescribed process: “Whether it is a failure management strategy or system engineering V or you're moving from one acquisition process or phase to another, you don't to have to reinvent that.” Also:

> I need to isolate the scenario for the learning objective and be able to kind of tweak it based on the learner and then see that multiple times until he gets a pattern of recognition down so that he can go ahead and deal with uncertainty, because he has a pattern of recognition, he knows what it looks like and he knows what the possible outcomes can be.

Stephen noted his personal growth in anticipating uncertainty, especially after having to recover after a failure or embarrassment:

> You see an older designer and they look really confident and they look really sure of themselves and they look really relaxed…being put on the spot a few times. When you go out and you present something and you didn't put too much time into it and you didn't really fully prepare to present it and you show this to somebody who's been there and done that, they're going to ask you questions that start off really benign and then they circle it…They're leading you into the gotcha question. Then you just sit there and you have nothing to say. It's a pretty horrible feeling. You feel really stupid and unworthy, but they know because they've been there… In real life where we live, you're going to make mistakes. Just don't let it get

you down. Just try to learn from your mistakes… you learn how you work best.

4.3.5 Category 5: Resilient

For Resilient engineers, uncertainty is a fact of life in the business, and for the items within their control, they know how to get the right data at the right time at the right fidelity from the right people in order for them to make the big decisions. They may even be in a position to "lead the market", or make company-culture-changing moves, because they have increased their engagement with key stakeholders, a key habit of human-centered design and empathic design (Zoltowski, Oakes, & Cardella, 2012). Their emotional response to big moves is that they "have gotten over it", referring to the criticism and resistance that typically follows project changes.

Resilient engineers describe a trusting engagement of their teammates and other stakeholders, making sure their teammates have the resources, authority, and courage to investigate parallel solution paths. The engagement of their teammates and stakeholders is early in the design process and significantly sustained throughout the process. In most of these transcripts, the participants used "we" instead of "I" to describe the path to solution. The complexity of the design projects is such that epistemic, ambiguous, aleatory, and interaction uncertainties are all present, and the best management skill is to engage large teams because an individual Resilient engineer cannot do the work alone.

The participants whose transcripts compose this category are Alonso, Duncan, Malcolm, and Peter. Alonso has 16 years' experience and Peter has 32 years' experience. They all have very definite leadership roles, which we can assume they earned because of their continued demonstration of proficiency in managing people and projects successfully.

4.3.5.1 Forms of Uncertainty

The participants whose experiences categorized the Resilient group identified epistemic, aleatory, ambiguity, and interaction uncertainties, with the greatest concentration on interaction of stakeholders inside and outside the design projects. In these transcripts, whole businesses may be interacting, with their own agendas and resources possibly in conflict or being kept confidential. Wherever data is available, Resilient engineers expect their teams to do their best to make sense of it.

Alonso describes his role as: “Leader of the Analytical Integration Team, that is a team that manages all the different design aspects such as handling qualities, dynamics, aerodynamics and simulation.” Because of the new configuration of aircraft, Alonso’s team encountered phenomenological uncertainty in a new maneuver that necessitated an investigation: “We have had specific problem in a certain maneuver and we experienced very high load unexpected… almost like an accident… What we have to do is go back and find the cause.”

Alonso speaks about boundaries of the problem as a guide of where he should concentrate his efforts: “you have many different areas that you can follow. Another important part is to limit or cut at some point, the boundary of your investigation and then solution of the problem…I have to do these three because this will give me the maximum and the minimum.” Here, he is referring to pursuit of the largest influencing factors under the control of the designers to mitigate the consequences of this new maneuver as the boundaries.

In particular, Alonso reflected on experiencing interaction uncertainty when his organization moved between countries: “we had to restructure the company… organizational wise because that was a lot of uncertainty in how to manage the problem and now we are in a different country with people on both sides of the ocean…in the US I’ve seen that there is more work then separate and then going together…We did away almost with the word meeting because people are meeting all the time and there is a continuing interaction but sometimes it can be chaotic.” This is different from Miranda’s and Silvia’s experiences, as they were individuals moving between countries, and Alonso moved an entire organization. So Alonso is aware of more varied forms of uncertainty here.

Duncan describes himself as having a systems view of design: “you've got all these people who are specialists in all these different things and they're great at that, but some task are just better handled if you looked at it from our systematic standpoint.” His high level view of design allows him to see how his company and his customer may interact: “you're waiting for some new program to come about or you're actually trying to form the business in the first place and you're working with a potential customer… you can get the requirements tuned to the strength of your company.”

Duncan described his design process as a mix of textbook processes and a personally-styled approach of making decisions in what concepts to pursue and develop:

> After the requirements, of course they'll eventually turn into specifications, but then it's trying to get those bounded enough so that you

can then come up with what your initial concepts might be… at the very beginning then you do make a conceptual design you make the decisions that I would be making as the designer ahead of time before I really talked to anybody else, assuming they all have a general understanding of what the requirements are… Then there's a whole other set of decisions that would then come up is when you start showing your things to management and they make their call. Then there's the whole decision that pops up when we as [company3] will be talking to the government or the customer and what happens then.

Duncan noted the indispensability of iteration like Abraham mentioned because an engineer can get fixated on one's own idea, like Nathaniel mentioned:

> The initial concepts, you're testing those out. I guess the biggest thing for us is the iterations with it… More often than not it's not usually the best answer so then there's different iterations trying to optimize to get a better solution… From a designers standpoint maybe there's some technical judgement calls about things you might want to do, because it's kind of your baby… there's a distinct style… the artistic part of it.

Malcolm described his career trajectory as being in the right place at the right time with the right willingness to take the work. He experienced several transitions as aerospace companies acquired other companies. He found himself entering programs at various stages of completion, such as conceptual design, developmental flight test, or close to transition from engineering development to manufacturing. Now Malcolm describes his senior program manager job as: "to make sure that we execute to, we have a statement of work, and we have a procurement spec. I have to make sure that the overall team is meeting those objectives…We have to have a structure in place to make sure that ultimately we fully meet these requirements that we signed up to deliver."

Malcolm typically presents several options and associated assessment strategies for meeting design requirements: "Usually, we present multiple options; usually they want to see a risk posture of choices… at the beginning of the project, you identify 'these are our requirements' and then you map out 'how am I going to verify every requirement that I own?'… Some of them can be verified with analysis, some of them will be similarity from similar programs, some of them can be in simulation labs, some of them will require flight test or other type of test data."

Malcolm specifically noted the "risk posture" of companies and the uncertain interaction of risk posture with the buyer:

> You have to understand the risk posture of your company and of the various divisions within the company and the various players. [company4] as a company is extremely risk averse. They will not lean forward hardly at all; they're always going to take the low-risk answer… This culture, which usually starts at the very top, the CEO level, tends to flow down. If the CEO is risk intolerant and profit is everything and they don't want to risk that, they want steady cash flow and so on, it's going to flow down through all the levels and it quickly becomes known that you do not tolerate risk… take those risks and assume they happen, which means

> baking them into your plan. What you do is you increase the cost… You got to be careful here because you could put yourself out of business.

Malcolm, like Curtis, thinks of uncertainty in terms of risk, and risk is divided into the typical top three constraints: cost, schedule, and performance or technical aspects. He is not the only one making the decision on these constraints. He said of technical or performance risks: "If it's a technical risk, what we tend to do is bring in our technical teams… if there's a technical problem, I'll work with my engineering managers. And we'll assess, 'do we have the necessary expertise to answer this?' ...sometimes we had to hire external SMEs." He said of cost and schedule risks: "that's more in the domain of the program management team. Just based upon experience and knowledge, you know what works, you know what doesn't because of your time and working over the years. You're able to make schedule assessments."

Peter advanced from engineering into leadership roles quickly, first taking technical responsibilities as a manager and then transitioning to leader responsibilities. He obtained a breadth of experience within a company: "I actually worked in the factory also which I think really helped shape me as a leader… how decisions are made in other parts of the business really help shape you for making decisions as a leader." He obtained further breadth of experience between companies: "took a great opportunity here at [company3] to be the CTO at [company3] which has really shaped me as a global leader not just as a more focused product leader around a certain element of portfolio."

Peter has significant decision-making responsibility which he takes very seriously and desires to pass to the next leaders. He said:

> I would say it happens almost every day. A lot of it comes down to, I think, intuition and judgment because I do think if I take a step a back, one of our biggest problems in our workforce today is not making decisions. We're ineffective at making decisions… what is the information that's necessary at what fidelity level to make a decision and once you agree that this is the information and the fidelity, making the decision is easy. Making sure that it encompasses everybody's stakeholders requirements around it… Not all of them were successful but you can always recover from a decision, you can't recover from no decision.

Peter sees a host of interaction uncertainty sources that other participants did not mention: commodity prices, foreign exchange issues, locations suitable for manufacturing, and the customers in their own contexts. He said: "Do we really understand how and what products and services they need for them to make and be competitive in their market space. A lot of our customers compete against each other which makes it even more difficult." Global and political events are also uncertain:

> There's ambiguity. There's volatility. There's churn… Understanding the markets, understanding the pending strength of the dollar, understanding the talent of our individuals in the region for the region… ambiguity around that because who could've ever said that from [country4], which was growing at 15%, is now really they say 7 but it's really around 2… the president would say and tax business people that use business jets… don't know what the workforce demographics are going to be.

Peter sees design as far as 20 years away that may become high priority because it has been matured by designers 3 to 5 years away from delivery. He said:

> On the technology front I don't think we have as much as a challenge as people may think… what is in the incubation state and really understanding what are those platform agnostic technologies that we see that eventually could lead to some differentiation in our product field. And you have to invest in those also so there's a wide lens of looking at kind of what's really emerging and how those things really trend itself into our product portfolio or adjacent markets that we'd be interested in. They could be 10, 15, 20 years out… product infusion in the next 3 to 5 years and then making sure that you're investing appropriately to mature the technology and the manufacturing at the point where the business decision is needed.

Peter sees long term aspects of the business that allows him to predict the significance of a trend, especially related to economic cycles and disruptions:

> I'm a big believer if you missed that window, and they're cyclic windows, what you invested in today is probably obsolete by the time you get the next opportunity… Once you get the product into the workplace and industry it usually stays there… it's very hard to displace an incumbent, it really is. You have to beat the incumbent by more than just the baseline cost price… logistics, everything that goes along with once you have that infrastructure in place… purposing and making sure that our decisions and

> our investments are aligned with buying decisions and timelines associated with our key customers' decisions are really the element that we continue to push on… how do you get in front of that market… investing in new products as the cycle is coming down and then when it bottoms out you're on the incline and the inflection point that we start to bring new products in as that market recovers.

4.3.5.2 Team Engagement

For Resilient engineers, immediate distribution of work to several teams of engineers is the primary design process they follow. The projects and objectives are simply too large for one person or a small team to have all the necessary specialties. Resilient engineers are different from Robust engineers in that Resilient engineers have a positive and confident view that they have the best people working the design problems to provide them the data they need to make decisions. Resilient engineers have the added responsibility of interacting with outside stakeholders, so they apply their intuition, built from years of experience, on those interactions.

Alonso immediately planned a team effort to investigate several possible influencing factors simultaneously. He expected that these parallel efforts would provide indicators of relative influence and then he could provide further direction to the team. He said: "it was my decision in the end on how to proceed in this. My specific role was to develop separately with every separate functions… To develop a path on how much going deeper and how to go in deeper on these aspects":

> How many other aspects of the same problem you have to look…They see was this the worst of the worst cases. Trying to define a limit of the variable coming from something that is not totally realistic…We put this cases and that was something very idealistic because you didn't consider all the feedback from the other disciplines…That was something that allow us to see at least where were moving… I let it go, this person reiterating on his design. Only at the end, I did the merging of these two world that this point have done quite separate work only towards the end that they were merged to demonstrate that everything made sense.

Alonso’s main responsibility is to keep his team talking to each other until there is enough actionable data for him to make a decision: “they need to continuously to exchange their information. You have to drive this and you have to actually to take the information and give the information... Making sure that this was happening and actually that all these areas were talking to each other. Then decide when to stop that was the important part because this could go forever, it could never stop.”

Alonso described his parallel team efforts in another way: “I knew that I had a couple of weeks just to investigate every different area and see all the different problems…In the beginning my team was good to have everything going on separately and then I started to close the loop and continuing with two or three big items.” Alonso noted carefully about having Subject Matter Experts on his team: “if you don’t have with you I mean good people you don’t go anywhere.”

Alonso remembers his prescribed requirements but also expands the list depending on the new knowledge his team gained, and continues to demand proof of meeting the requirements: “I have demonstrated that what I’ve designed satisfies some objective that I have decided… I've also found that what was designed before didn’t satisfy something else that I didn’t know. I had to put another 20 percent of requirement before I didn’t have… I have to re-verify that everything that I had done before wasn’t changed.”

Duncan’s strategy is to gather evidence right away, even if it is just an indicator, so that he does not experience the “gotcha” moment that Stephen mentioned. He also advocates assembling a supportive team:

> The big thing is you're always trying to get yourself educated enough and rescope the problem… You never want to get into any meeting where your answer is, ‘I don't know.’… so that it doesn't get to the point where you're just coming in and you don't know. Part of it is trying to minimize that. If you don't know, then you're setting up things that do let you know. That's why you may do some outside analysis... Getting as well versed as you can on what it is you're working on and then certainly trying to surround yourself with people who are like-minded.

Duncan has a team of specialists and that includes his customers. His design specialists, like Nathaniel noted, can remove a few cycles of iteration. He also maintains communications with the customer as a means of reaffirming the requirements, but he does not describe it confrontationally as Frank did:

> You have the formal requirements and everybody goes through and so that's been formally issued… certain people in the company who specialize in dissecting that… it's also working with the customer to make sure you're still on the same page with them… you can get "the older" engineers who've seen a lot of things and know a lot of things… have enough experience that they could look at it and probably give you a pretty good estimate of what it could and couldn't do and tell you whether they think it will pass muster… If you're seeing it from them and you're seeing it from your A-team of people then they feel pretty confident.

Duncan sees internal and external interaction uncertainty within the company's hierarchy and with the customer, where the priorities of each party may be in conflict:

> Prior to probably coming from a customer, you've probably been told a few things as to what they want… there's a little bit of a hierarchy… program manager wields a lot of power…management has certain expectations… our plan as a corporation on how we want to solve this… what the customer told you in the requirements… That one pretty much overrides anything… You're juggling both of those.

Malcolm's team experienced significant schedule uncertainty that tied closely with performance uncertainty, which would ultimately negatively affect the customer: "One of the problems we've experienced recently is there's been problems on the jet as far as [company3] providing us the time we need to be able to test. And it's impacting the way we can execute because we're not getting the flight data and that feedback loop, we're not able to incorporate the changes and do the verification we need… fleet was going to be grounded for a period of 4 months."

Malcolm's response was broad coordination on a plan: "We had to make some decisions. We ended up working closely with my [company3] team, their program manager came out, we sat down with my team, some of my counterparts within [company4]. We developed a plan of recovery, we vetted with [company3]. We presented it to the executive management. They gave us feedback and adjustments." The secret to successful execution of the plan is: "It's all about getting, within this span of authority, you have to find the decision maker who has the stand of authority to truly make and own that task. And you got to put it at the right level." The success was obvious to the customer: "they heralded that meeting as an example of supplier-prime contractor, meaning, [company3], [company4], this is how we should be working. We're finding answers."

Malcolm again emphasized his lateral and vertical team providing him the knowledge he needs to make decisions:

> Usually the key here is, if decisions are going to hold, you have to vet them. A lot of junior PMs move and make decisions very quickly and if they're not vetted… looks like you're an idiot. So it's usually best to have a very broad coordination, make sure everybody's aligned before it ever gets to that executive review. Then you're presenting a cohesive team review that's been fully vetted by all parties… what's the appropriate level. If this decision is going to be elevated all the way to the vice president level, for

> example, I can't just engage the lower level stakeholders, I've also got to engage their management chains all the way up that will be reporting to that vice president.

Malcolm's attitude to managing others' uncertainty is one of partnership:

> The suppliers will say 'it's not my problem. I have this statement of work, this is your problem, it's not my problem.' And they have very rigid boundaries… really want them not to be so rigid. You really want them to work closely with you. You want them to have some level of flexibility to give and take. It makes the process much easier… show that we were in a partnership, not in a supplier relationship… things don't go according to plan… So we've had to do adjustments to that plan along the way in order to be flexible, in order to come up with an option.

Peter sees his teammates as stakeholders, quality leaders, manufacturing leaders, engineering leaders, research centers, and the sales force. He especially relies on his sales force for actionable data about the customer: "our customers are becoming much more educated on the overall lifecycle of their product. Our sales people and our engineers are really working very hard to be very integral to their key relationships with inside those customers."

Peter noted the indispensability of his teammates to manage their subject matter in order to provide him actionable and reliable data: "the biggest element in the product design cycle today is that we don't have all the right people at the right time ensuring that the product portfolio is moving at the pace it needs to… really makes you think a lot different for where you put people and where you're going to invest in your product and how do you get more stability in the currency exchange where you can insure that you don't have the volatility."

Like Joel, Peter sees design happening over such a long period of time that engineers may become attached to the work, like Nathaniel and Duncan point out, "I'm pregnant with the idea, it's my baby" that Peter must face his team's attachment: "engineers will fight to the end to maintain and give you every argument why they should continue… you have to make the decision where do you get the best return for that investment… you have to get past a personal part of the decision." However, Peter has a high level vision of repurposing designs for which there has already been investment: "I'm a big believer is that at some point some of the things that we worked on it just may not be the right time and some of the technologies that we work on may be applied somewhere else… we don't throw everything out… We shelf it, make sure we know where it's at."

Even though Peter said he relied on judgment and intuition for some decisions, there are decisions for which there is evidence, and he reflects on the quality of that evidence in order to enhance his intuition:

> I think you'll find in industry that the depth of the information that's actually being looked at is probably not the depth of the information that really needs to be looked at… I'm a big one on lessons learned… you start to look for an inflection point when the program starts to look like there is something going wrong, you stop and you pause there and you really start

to look at what information were people looking at at that time period… looking for inflection points and looking for the information that was actually being viewed… That's usually our biggest problem, I think, in the industry is that we don't focus on the information and the people that is necessary at the time to insure that we're at the level that we need to be during the program.

4.3.5.3 Personal Response to Uncertainty

Resilient engineers tend to formalize and externalize their thought processes for design and managing uncertainty. They have an altruistic motive to preserve the hard-earned knowledge they have. It also allows for these thought processes and data to be examined and evaluated by others for further refinement, a welcome step of the design process. Resilient engineers are even optimistic about uncertainties in design because they have decade-long views of products being matured.

Duncan's approach to managing uncertainty is to stay abreast of the current published data and new possibilities, especially coming from his teammates:

> Come in as prepped as you can… knowing the literature. Look at what has been done with what's out there… you also want to be flexible enough to flex with something that may not be exactly what you think it might be… Then when we get to the different people in different disciplines and different specialties and they're certainly keeping up with their particular

> field… To be in that particular role you had to be versed enough to be able to talk to the discipline specific person.

Because of the volume of data and uncertainty that Malcolm encounters, he applies limits and boundaries of what is acceptable:

> As long as you're inside the upper bound and lower bound, you're ok. If you aren't and you have a deviation, that's when you have to go and make changes… anything that's critical, we have boundaries for what's acceptable or not. What that does is it makes, whenever you do the analysis, it eliminates the decision…you identify your critical parameters, your engineering parameters, and what the margins are for those, so that you know if you have success or failure. The other uncertainty comes in, the cost and schedule, is a bit more amorphous. It's usually managed through the risk process.

Malcolm has several tools at his disposal for formalizing risk, like Abraham, Joel, and Frank had mentioned. Like Curtis and Edmund, there are costs associated with continuing to reduce risk, so Malcolm has responsibility to determine the stop point, like Alonso had to do:

> There will be company guidelines. The company will write a risk policy, and their risk policy is heavily influenced by their corporate culture… variety of tools. Some companies have homegrown tools…. we take a look at everything we've learned over the last quarter and we do a

> bottoms-up estimate-at-complete... you typically use what they call a risk cube… plots consequence, the impact if it happens, versus probability… It costs money any time you do a mitigation plan or anything about it, it costs money to maintain this process. And they recognize they don't just want to throw money at it and do everything. When you have a moderate risk, most companies require that you have a mitigation plan in place.

Malcolm anticipates uncertainty and has plans in place for the unexpected: "You're always going to be getting surprised… When you're in the design and development side of the house, you have to be prepared. You're working in a very different environment. You're going to have surprises… if you have a robust risk process, you can hopefully, if your risk process is working, what should happen, you should identify these potential scenarios before they occur… you identify contingencies." Malcolm has a history of relative success in predicting the consequences of uncertainties: "probably 60% of the things that have happened, have happened within the risk process and we have been able to execute those contingencies… 40% have come up where either we simply didn't think of them, or the risk plan didn't fully foresee the magnitude of what could happen, or the contingency wasn't sufficient enough to be able to deal with it."

Malcolm's personal approach to uncertainty has been tested by failure and he recovered:

> They're not doing their job if they're not having failures as well as successes…we ended up crashing both of [prototypes]. And that was even with all the plans we had, all the contingencies… we executed to the best

> of our ability…I took a lot of responsibility for that failure, I really did, and it took me a while to get over it… you're measured on how you react and how you handle them. You also want to be as proactive as you can… you need to be as transparent as you can, you need to identify the correct level of risk… you shouldn't be taking it personally. You have to end up taking the cards you're dealt, you do the best job, you make sure your communication is crystal clear as you can. What happens, happens… They have to recognize you cannot do this all on your own. You need to be reaching out, networking, have allies, have mentors in place.

Peter noted his personal approach to uncertainty as a balance between intuition on risky decisions and getting his team to provide the right data to make a decision:

> Very carefully. It's hard. At some point you have to go with intuition on some of those ambiguous ones… You can't be risk-averse on everything and I think there is this balance on risk-averse and intuition and judgment and making sure that you're not waiting for the market to come and you're leading the market to get to a place that you think is going to be viable… but there is so much ambiguity but you have to at some point have intuition, judgment in everything… How do you really insure that you're asking the right questions at the right time? What questions should you be asking… are you asking the right questions at the right time at the right level.

4.3.5.4 Reflections on Learning to Manage Uncertainty

Participants in the Resilient category found that their personal response to uncertainty is not hidden, that others are watching them. They are also watching themselves and discovering that they have improved both their awareness of forms of uncertainty they encounter in design and accompanying management strategies. They have become comfortable managing their own uncertainty and can now help others manage their feelings and uncertainties.

Alonso noted his personal growth in managing uncertainty: "I learned now how interconnected things are… when you have to press and when you have to wait… you have to give some time to the idea to evolve…variables can be even interconnected between themselves… There are stronger variables and less strong variables but you don't know this at the beginning…even if it is uncertain it's still something that you manage." Another aspect is confronting his own assumptions: "spoiled basically by your own pre-concepts…sometimes you get stuck on something…you leave something outside just because you don't have a good relation with the person… so you have to be open."

Duncan identified his growth like Frank had: "You go through each one of these steps, probably fairly systematically, and I think the more experience ... You still follow a process but you jump to things pretty quickly… iterations internally may go around a lot quicker… but the more you've done it ... There is a process but you can run through the steps probably a bit quicker and it probably gets more merged." Duncan now coaches younger engineers through design problems:

> We want you to get comfortable with the chaos… You may not know all the answers, but again, you're comfortable with dealing with it and making assertions and assumptions and trying to be able to back up those assumptions so you can move forward… How would you do any real complex thing? You don't try to solve it all at once. You try to get into those simpler parts and eventually you get the whole thing solved and coming together to a solution… If you came in new, you were probably paired off with somebody who's a bit more senior and you probably are going to pick up some of the habits that they had. If it's valid and if it looks like the people are respecting them and it's something that the company likes, then you make pick up those different habits and you put your own spin on it too.

Malcolm has also been a teacher of risk management at the corporate level. His lesson includes the major points summarized in his transcript, particularly one's personal response to uncertainty and failure:

> Your management is going to be looking at you at how you responding, and how you're executing once that occurs. They're not going to be looking at you and blaming you because it occurred… over communicate, think broader… you want to be more inclusive… build a broad consensus… categorize the uncertainty… you have a stoplight chart… trending lines, is it getting better or is it getting worse… When we talk

> uncertainty, it's measuring versus that baseline… All the customer deliverables, every piece of it.

Peter learned how to manage his own uncertainty and others' uncertainty from observing a mentor in action:

> 'What I'm going to teach you about is around dealing with people, dealing with ambiguity. How to interact and how do you message? What should you really be paying attention to? What's the depth of, if you're leading something what's the depth of what you should really understand?… Don't ever worry about being an expert in every area but you have to at least know what quadrant the answer should be in…. messaging and understanding the level of fidelity that I should be paying attention to'… I shadowed him for quite a bit in a lot of the senior meetings.

4.4 Differences Between Categories

Since the goal of phenomenography is to find variation of experience, and the outcomes are logically related, typically by a hierarchy, the differences here imply a learning trajectory. This learning trajectory answers the second research question in Section 2.8.

4.4.1 From Category 1 – Brittle to 2 – Plastic

One of the key differences between Brittle and Plastic engineers is the amount of fear they discuss; Brittle engineers are considerably more emotional than Plastic engineers. This may be related to the dimension of teamwork; Brittle engineers describe mostly their work as individual projects and Plastic engineers are beginning to leverage knowledge of their teammates, however superficial it may be. Brittle engineers are aware of the fact that there are subjects they have not learned, but Plastic engineers are aware that other teammates may know that subject, so Plastic engineers have reduced their negative emotional response by convincing themselves that someone nearby will know what they do not know. Brittle engineers, however, have not yet mastered the ability to ask someone else for help and advice.

Brittle engineers have not made informal peer review a part of their design process yet. Brittle engineers are trying to perform to summative reviews rather than formative reviews (Pellegrino, Chudowsky, & Glaser, 2001). Brittle engineers think of reviews as a pass/fail moment and their emotions are tied to that result; for Margaret and Philip in particular, they fear that failure will terminate their careers. On the other hand, Plastic engineers seek peer review regularly with less fear of failure. Rather, Plastic engineers acknowledge that they may have made a mistake and another perspective is valuable to catch it.

Because of Brittle engineers' focus on summative review and the fear of failure associated with it, they tend to push decision-making to their immediate superiors. Plastic engineers, on the other hand, have learned to judge themselves first and assemble a defensible position. Plastic engineers still rely on superiors because they respect their superiors' breadth and length of experience, but their superiors are now teammates instead of judges to them.

Brittle and Plastic engineers both experience epistemic uncertainty, and if they gained knowledge, then their uncertainty would be reduced. Brittle engineers tend to continue to learn individually and suspect that the "whole story" is hidden. Plastic engineers have a different attitude that they are fairly certain that everything has been tried before, and now that they are "in the real world", working for pay, they have the freedom and responsibility to ask questions of others and expect to get the answers.

Brittle engineers are named thusly because their response to uncertainty is to break easily emotionally. Plastic engineers are named thusly because their response to uncertainty is to make design moves in a certain direction, and when they have reached the end of the checklist, they deem their uncertainty eliminated. The checklist to Plastic engineers is some process defined by other more experienced engineers as the external embodiment of knowledge, and that is satisfactory to Plastic engineers.

4.4.2 From Category 2 – Plastic to 3 – Tolerant

The difference between Tolerant engineers and Plastic engineers is not the difference in years of experience but that Tolerant engineers view themselves in a network of engineers, with themselves having a systems view or broad view of the design problem. A Plastic engineer's view of the design problem is that he is looking up the hierarchy for people with answers, whereas a Tolerant engineer looks across the hierarchy and can assemble a team in a day, but it will take the team more than a day to converge on a solution. A Plastic engineer's view is that a design problem *could* be a team effort, whereas a Tolerant engineer's view is that a problem *must* be a team effort.

Now that a Tolerant engineer must function in a team because of the complexity of the design tasks, the Tolerant engineer now experiences ambiguity uncertainty in addition to epistemic uncertainty, where ambiguity comes from the team and their customers. Ambiguity is present in communicating in oral, written, and visual forms. The Plastic engineer, on the other hand, is not aware that any communication could be interpreted in several ways, depending on the speaker and the audience.

A Plastic engineer may feel disconnected from a design task, especially if they are following a checklist, because they are relying on others' experience and knowledge. A Tolerant engineer, on the other hand, feels a significant investment in the design, a sense of ownership and responsibility. A Tolerant engineer, then, feels empowered to make a decision and enforce it, whereas a Plastic engineer may not have the strong sense of wanting to enforce a decision in a design.

It is at this point that a Tolerant engineer may be a Subject Matter Expert in others' views. Tolerant engineers have a deep understanding of fundamental principles of physics and engineering and these principles are their guides. Plastic engineers, on the other hand, may use what other people simply tell them as their guide. Tolerant engineers now have a view of at least one system, recognizing that there are many other systems, but the other systems are not within their purview of responsibility; rather the Tolerant engineer can and will converse with other system owners, where boundaries between systems may be negotiable. To a Plastic engineer, boundaries between systems are non-negotiable.

Tolerant engineers have an experimental attitude, in that they expect that some things will fail, whereas Plastic engineers tend to believe that following the checklist will catch and prevent failures. Tolerant engineers are named thusly because they are tolerant of the possibility of failure as part of design and the certainty that uncertainty cannot be eliminated.

4.4.3 From Category 3 – Tolerant to 4 – Robust

Tolerant engineers appear to take on individual work still and mention teams in general, but without a strong emotional response to team aspects. Robust engineers have taken a step up to bear responsibility for team performance, and that new responsibility may be a cause of anxiety. Team performance now refers to teams of teams managing systems of systems. Robust engineers now have an emotional response to both project and team, because they view their teammates as responsible for certain systems. Robust engineers experience conflict between teammates and have the responsibility to manage that conflict to finish the design task. Robust engineers are named thusly because they have enough managerial courage to get the design job complete to design requirements and specifications.

Robust engineers can reach back to the habits of Tolerant engineers and ask for evidence as a means of confronting another teammate. Sometimes, Robust engineers rely on their intuition, which they have described as being developed through repeated experience. Tolerant engineers do not use the word *intuition*. Tolerant engineers are not yet completely comfortable with their level of experience, whereas Robust engineers are very comfortable with their experience, though it may not be entirely reliable.

Overconfidence, mentioned as part of "bad" decision-making, seems to be part of intuition. As a comparison point in aviation, it has been shown in Figure 4.4.1 below that accident rates of pilots with thousands of hours increase at 3,000 to 4,000 flight hours (Aircraft Owners and Pilot Association, 2007). But beyond 4,000 hours, accident rates decrease, perhaps indicating a humbling experience that caused the pilot to return to real data instead of intuition as the evidence for making a decision.

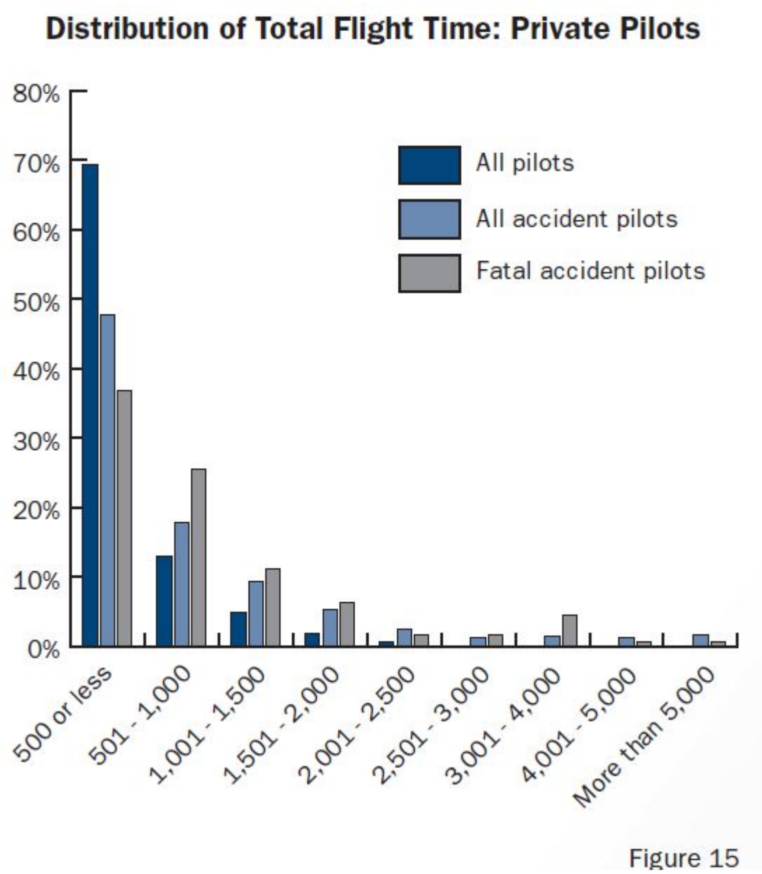

Figure 4.4.1 Accident rates of private pilots as a function of hours of flight time, reproduced from the Nall Report.

From Table 2.3.1 description of expert teams, Robust engineers may have all the elements except *develop a sense of teamness, collective*. A Tolerant engineer is also missing *have strong team leadership* as a personal characteristic that distinguishes a Tolerant engineer from a Robust engineer. Either way, the Tolerant and Robust engineer would be viewed by peers as a good engineer.

4.4.4 From Category 4 – Robust to 5 – Resilient

Resilient engineers have mastered expert teaming in Table 2.3.1 especially by the trust in *Develop a strong sense of "collective," trust, teamness, and confidence*. Resilient engineers spoke with the plural voice instead of singular; that represents the extent that they integrated themselves into a team. For Resilient engineers, trusting teamwork is the only way to manage all the forms of uncertainty that they encounter, whereas Robust engineers may be sheltered from some forms of interaction uncertainty, such as changing market demands.

Resilient engineers are named thusly because they have appropriately managed their teammates to recover from a realized risk item, which in some cases was high severity and unpredicted. Joel in particular is on the edge between Robust and Resilient, because the design teams he had were much diversified, but his emotional response was quite strong, whereas the participants in the Resilient category have a comparatively subdued emotional response.

Resilient engineers also differ from Robust engineers because Resilient engineers have almost an optimistic sense of the positive impact of the designs they are delivering, in that they could "lead the market" and shift their buyers' opinions. Robust engineers, on the other hand, can and do fix the problem to finish the design task, and that is enough work to handle. To that end, Resilient engineers spend significant time crafting their message through the ranks and to the customer, whereas Robust engineers concentrate on *what* they say instead of *how* they say it.

4.5 Relationships Among Categories

It is typical in phenomenography to represent the relative comprehensiveness of outcome categories graphically. While Category 2 is more inclusive of types of uncertainty than Category 1, Category 2 is exclusive of Category 1 with regard to the participant's personal approach to uncertainty and skill in team engagement. Therefore, Category 2 is represented higher and to the right of Category 1, but not overlapping Category 1. The same follows for the relationship between Category 2 and 3 and so on.

In Figure 4.5.1 below, a mathematical layout of axes is applied, where higher and to the right of the origin implies a greater value. The first dimension shown horizontally is the complexity of the design problem, where the indicators of complexity in the transcripts are the greater number and greater variety of forms of uncertainty the participant is aware of. The second dimension shown vertically is the increasing necessity of team engagement as a significant means of coping with the increasing uncertainty. The colors of the discrete values of each axis are meant to correlate with the colors of each category. The third unifying dimension of the five categories could be read like a typographical map, where a colored outline represents a constant elevation, and here it represents a constant category.

For consistency, in Figure 4.5.1 below, the forms of uncertainty are named from Thunnissen's taxonomy's first level, but the details of the second level are not shown for simplicity's sake. Epistemic uncertainty is present throughout all the transcripts, so its stripe goes from origin to the far right. Tolerant, Robust, and Resilient engineers experience ambiguity, so its stripe goes from Tolerant to the far right. Resilient engineers are aware of all forms of uncertainty, so there are four stripes of uncertainty along the independent axis.

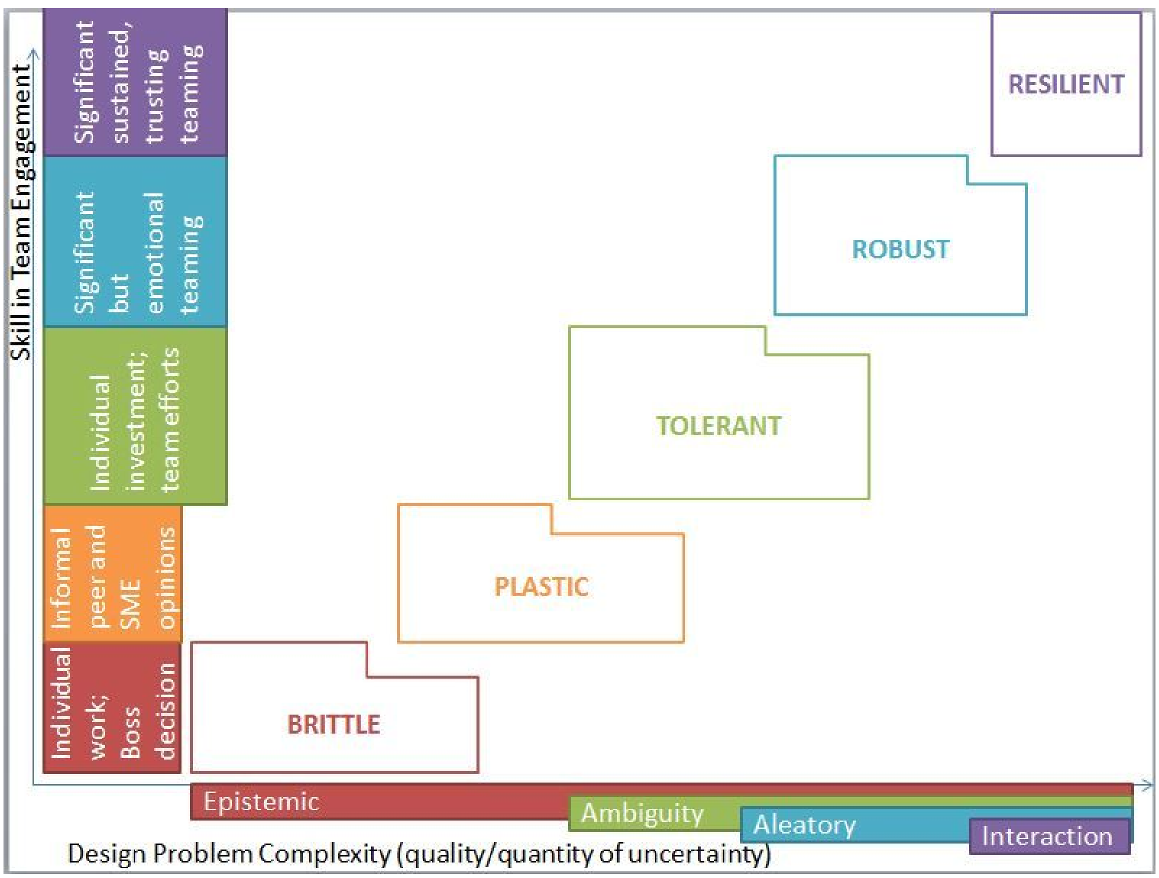

Figure 4.5.1 Outcome space for ways of experiencing uncertainty in aerospace design decisions.

In Figure 4.5.2 below, the names of the participants are located in the categories to demonstrate some stretch in either dimension within a category. The skill levels in team engagement are shown as discrete values and should be interpreted thusly. The vertical distance between participants within a category represents a small difference in skill in team engagement. The vertical distance between categories is significant. The superscript number next to each participant's name represents the years of experience listed in Figure 3.10.2 in Section 3.10.1.2.

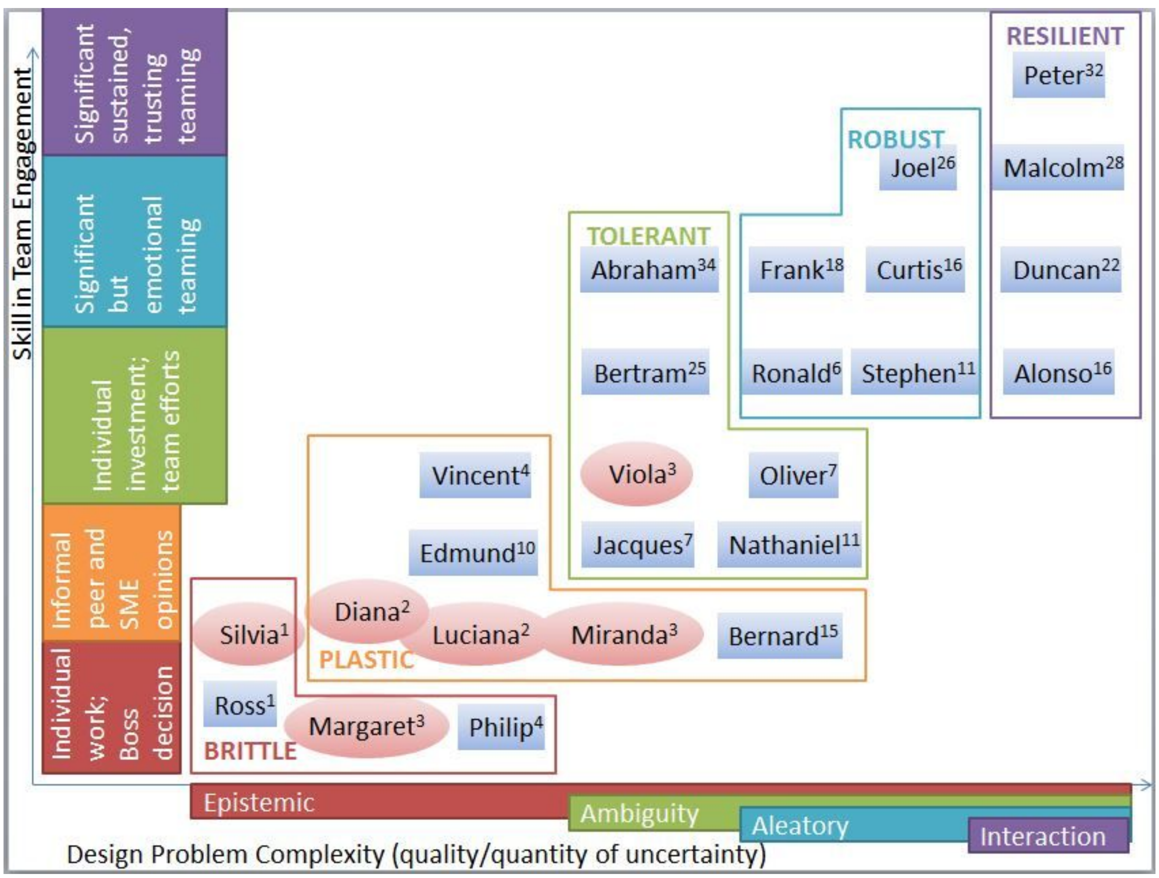

Figure 4.5.2 Outcome space for ways of experiencing uncertainty in aerospace design decisions, with participants located in categories.

4.6 Summary of Categories

A summary of each category appears at the beginning of Section 4.3 above. It is repeated here in Table 4.6.1 for quick comparison. The colors correspond to the outlined categories in Figure 4.5.1. The third column represents the horizontal dimension. The fourth column represents the vertical dimension. The second column represents the categories, which I have called the third unifying dimension of experience.

Table 4.6.1 Summary of Category descriptions.

Category	Personal Response to Uncertainty	Design Task Complexity (Forms of uncertainty) Axis	Skill in Engaging Teammates Axis
Brittle	Uncomfortable with uncertainty or afraid of the consequences of being found ignorant by superiors; strategy or recourse is to push decisions to someone else, typically boss or team lead	Epistemic only; they are aware that there is subject matter that they have not yet studied	Individual work, and maybe some informal peer review
Plastic	Takes solace in the fact that most things have been done before in aerospace and that there will be someone more experienced available to assist; will take some initiative to gather new knowledge and to justify decisions to themselves first, but also rely on superiors for decisions	Epistemic uncertainty as the Brittle category, but also including schedule and budget constraints	Describes projects as team efforts, acknowledges that others have unique and complementary knowledge; peer review is desired

Table 4.6.1 continued.

Tolerant	Good awareness of uncertainty in the physical parts and systems is ever present and will never be eliminated, uncertainty also comes from customers and teammates in attempting to understand their goals and concerns	Epistemic uncertainty that can be reduced through planned and long term testing and experimentation; ambiguity uncertainty among teammates	Describes projects as team efforts, for which they feel a significant investment or ownership in a crucial part of the project
Robust	Anticipating the unexpected, willing to try new methods, processes, solutions, and looking for data instead of opinion to validate and verify new solutions	Epistemic, ambiguity, and aleatory uncertainties; decisions hinge upon having real data and not just SME opinions	Significant but possibly confrontational engagement with teammates and other stakeholders
Resilient	Uncertainty is a fact of life in the business, and for the items within their control, to get the right data at the right time at the right fidelity with the right people to make decisions and even lead the market	Epistemic, ambiguity, aleatory, and interaction uncertainties; interactions could be global/political, customer-vendor, or systems within a product	Significant and trusting engagement with teammates and other stakeholders; have the resources, authority, and courage to deploy teammates on parallel efforts to investigate

CHAPTER 5. DISCUSSION

Within each category, the demographics of the participants vary, suggesting that the essence of the experience of uncertainty is deep and broad. Within Category 1, there are men and women, students and working professionals, those with international experience and those without. Within Category 2, there are men and women, pilots and non-pilots, researchers and those in private industry, and one with international experience. Within Category 3, there is one woman; there are those with greater than 20 years' experience and those below 10 years' experience. Within Category 4, there are 4 pilots and 1 raw materials supplier, one with only 6 years' experience and several with greater than 20 years' experience. Within Category 5, there is one with international experience, and there are at least three tiers of job title represented. While some exposure and experience of uncertainty may be specific to the job title, there is clear evidence that an engineer's personal response to uncertainty is not necessarily linked to the type of company they work for or the years of experience they have.

5.1 Shape of Outcome Space

Categories 1, 2, 3, and 4 in Figure 4.5.1 have an L shape, implying that engineers may improve a little in their team engagement or improve a little in their awareness of forms of uncertainty, but that their personal response remains the same as others in the same category. Being able to manage uncertainty better personally does not solely involve an engineer becoming more proficient at modeling tools and becoming an individual Subject Matter Expert in multiple subjects. In order to progress between categories, then, an engineer needs to realize that the strategy for managing increasingly complex design problems must more deeply involve their teammates. Then, an engineer's personal encounter with uncertainty can become less intimidating.

It is clear from the participants' varied experiences that the aerospace business delivers complex systems that integrate into systems of systems. Category 2, 3, 4, and 5 participants are very clear on their relative location in systems-of-systems business hierarchy, knowing that they have customers and suppliers with competing and conflicting modes of operations and goals. These participants are effectively equating component systems (e.g., engine, hydraulics, or avionics) to people, engineeringdesigners who are responsible for those systems. Participants deem that making the owner happy is equal to making the system functional according to specifications. Therefore, participants make progress in bringing in larger numbers of people into their design process.

Because engineers of higher categories see systems as people, there is empty space in the outcome space. The empty spaces represent that it is not a successful strategy to improve an engineer's awareness of teammates' contributions independent of increasing awareness of forms of uncertainty in increasingly complex design problems and vice versa. Rather, an engineer's understanding of the value of teammates should improve simultaneously with increased experience of complexity of design problems. Similarly, as complex problems with increased levels of uncertainty are introduced, development of teaming and interpersonal skills is important. It is as if the aerospace industry with its high level of complexity is indicating that no engineer is expected to be an individual inventor but rather part of an integrated team in this competitive, global economy.

5.2 Thresholds Between Categories and Demographics of Variation

It is the personal and internal emotional responses that are the key differentiators of participants, more than their apparent awareness of types of uncertainty and their skill at team engagement. This aligns with the concept of "coping strategies", to suppress uncertainty, to acknowledge uncertainty, or to reduce uncertainty (Lipshitz & Strauss, 1997), where suppressing, reducing, and acknowledging are internal responses and these are manifested in outward activities, such as taking a gamble, soliciting advice, or collecting more information. It is these personal emotional responses that are named according to the analogy of physical materials' responses to stress loading.

The boundaries between each category are drawn to represent different personal emotional responses to uncertainty, and there is something unique about Category 1 that higher category participants have overcome. Category 1 – Brittle engineers may allow their strong negative emotion to hinder them from making progress on their design, hinder them from seeking to learn new information, or hinder them from taking on decision-making responsibility. Category 2 – Plastic engineers still encounter uncertainty, but they have developed at least one strategy, such as seeking peer or mentor review or viewing failure as a learning opportunity, that gives them the confidence to proceed with the design task. Category 1 – Brittle engineers seem to have the fundamental view that others around them are like judges instead of teammates, whereas the higher category engineers fundamentally view others as teammates instead of judges.

Category 3 – Tolerant engineers displayed almost no emotions in their transcripts. Whereas Category 2 engineers express their design process as serial, Category 3 engineers described their design process as several parallel efforts, where they are looking for the biggest influencing factors. Category 3 engineers are expecting that some factors will be more important than others, but at the beginning, they may not know which, so they remain open-minded and experimental.

Category 4 – Robust engineers have faced the possibility that there is aleatory uncertainty, which uncertainty that could not be reduced even with more knowledge. Engineers that deal with aleatory uncertainty here have operationalized it as *risk* to flight safety, cost, or schedule and have defined some acceptable level of risk. Robust engineers have figured out the inescapable importance of engaging other teammates in order to manage risk and it manifests in very frequent use of *we*, whereas Category 3 engineers are not always speaking in the plural. Robust engineers realize the matter of managing others' opinions and feelings in order for the others to be motivated enough to finish high quality work on the task. That is how Robust engineers get the whole design task completed, but it can be tiring for them.

Category 5 – Resilient engineers, especially Peter, Malcolm, and Duncan, have taken a step up from seeing only their coworkers as teammates to seeing the customer as much a player in the execution of the design task, a human-centered design view (IDEO, 2009; Maguire, 2001; Zoltowski et al., 2012). Peter and Malcolm were specific in reflecting on their switch from technical-centered to customer-centered design. It seems that the customer, prime contractor, and supplier interaction uncertainties may dominate the attention of Resilient engineers, and they know they have teams of capable engineers and others around the business to attend to technical matters. Resilient engineers have enough technical knowledge to stay abreast of the evolution of the solution, and they trust the process and the designers to converge on a solution, whereas Robust engineers may have some trepidation about converging on a solution. That is what separates a Robust engineer from a Resilient engineer.

While personal and emotional responses are the primary delineators of categories of experience, it does not mean that women are concentrated in one or a few particular categories. It is encouraging to see that although the female participants in this study are on the younger end of the spectrum, they are spread across three categories. It is a limitation of this study that I did not successfully recruit women who have been working 20 years and/or have leadership roles in order to confirm that women's experience of uncertainty in design decisions is no different than men's experience. With key researchers exploring the gendering of professions (Pierce, 1995) and why highly educated women are opting out of the workforce (Stone, 2007), it would not be appropriate to make assumptions about what all women would say about their design experiences.

Some participants with pilot experience brought a user perspective to the design process but other pilots did not make specific mention of it influencing their design decisions. Bernard (Category 2 – Plastic) and Curtis (Category 4 – Robust) were very clear on the impact of their pilot experience on their design process; they considered where information was coming from and how much information a pilot could take in.

However, Oliver, Stephen, and Abraham did not talk about it much. Ronald spoke more about his technician perspective than his pilot perspective. Joel talked about pilot experience from the perspective of considering flight safety of paramount importance because of personal friendships within the pilot community. However, pilot experience by itself was not a sufficiently distinct category for experiencing uncertainty in design and decision-making.

Participants with international experience made comparisons between cultures and they are spread across most of the categories of experience. Miranda and Alonso were specific in their awareness of cultural differences having an impact on their style and frequency of communication, which in turn affected how they manage the design process. Silvia and Jacques were specific about moving between cultures as having a positive impact on their confidence to engage in new circumstances. Margaret, on the other hand, compared the culture of private industry to the culture of research and academic environments, saying that her industry experience was more certain and comfortable than her research experience, primarily because in industry, she had a supervisor with a defined process. Peter did not make claims of global experience in the same manner as Miranda and Alonso, but Peter made specific reference to gaining a more global view as he moved from a prime contractor environment to a supplier environment. In all these transcripts, it is clear that cross-cultural experiences had noticeable impacts on the participants' awareness of uncertainty, a desirable trait for the next generation of engineers (Downey et al., 2006; Jamieson & Lohmann, 2009; K. Sheppard et al., 2004).

There is a fairly consistent correlation between job title (an indicator of level of responsibility) and category, where Category 4 and Category 5 participants had explicit leadership roles and Category 1 and Category 2 participants did not have leadership roles. Category 3 participants described responsibilities for which they have final authority, but they did not describe these as leadership roles. This correlation may be the result of participant self-selection, where they may have accounted themselves successful in the roles they have, and thus feel confident in disclosing their experiences for research purposes (note that no participant in this study described themselves as having been unsuccessful to the point of being removed from the job). Alternatively, those engineers that develop and demonstrate desired professional skills receive more responsibilities through promotion, which would lead to an expected correlation. These job titles, however, were not sufficient to predict categories and participants with similar job titles spanned categories.

Another expected correlation is between years of experience and category. All of the participants were still in the aerospace field so those who were not successful and left the field or were fired were not included in this study. It would be expected, therefore, that more years of experience would lead to more experience with mastery of uncertainty. This is shown in the data with a cluster of participants with 4 or less years' experience at the bottom left of Figure 4.5.2 and a cluster of participants with greater than 20 years' experience at the top right. Yet there are exceptions; Abraham and Bertram at greater than 25 years' experience are in the same Category 3 - Tolerant as Viola, with 3 years' experience. Ronald with six years' experience is in Category 4 – Robust with Joel at 26 years' experience. Somewhere in the middle between Category 1 and Category 5, the participants demonstrate a certain level of willingness to take on increasingly complex design tasks, and that internal willingness is the differentiator.

5.3 Expert Teams and Ways of Experiencing Uncertainty

While phenomenography investigates an individual's experience of a phenomenon, there is value to considering the teaming aspects that the participants in this study are aware of and mentioned, even though teams were not specifically investigated or observed in action. Referring back to the conceptual framework of expert teaming in Table 2.3.1 illuminates key differences for managing uncertainty in teams as shown in Table 5.3.1. Because no teammates from the same project were included in this study, it is not possible to uncover the outcome of *hold shared mental models* beyond the culture of aerospace in general as described in Section 4.2 Common Themes. For future research work, it is important to consider these aspects of teaming for identifying skills that students may intercoordinate (Fischer, 1980) in order to develop the higher level skill of managing uncertainty.

Table 5.3.1 Categories of experiencing uncertainty in design decisions compared to expert teams' outcomes and behaviors.

	Ways of Experiencing Uncertainty in Design				
Expert teams...	Brittle	Plastic	Tolerant	Robust	Resilient
Hold shared mental models	NA	NA	NA	NA	NA
Optimize resources by learning and adapting	Yes	Yes	Yes	Yes	Yes
Have clear roles and responsibilities		Yes	Yes	Yes	Yes
Have a clear, valued, and shared vision				Yes	Yes
Engage in a cycle or discipline of prebrief → performance → debrief		Yes	Yes	Yes	Yes
Have strong team leadership				Yes	Yes

Table 5.3.1 continued.

Develop a strong sense of "collective," trust, teamness, and confidence					Yes
Manage and optimize performance outcomes	Yes	Yes	Yes	Yes	Yes
Cooperate and coordinate				Yes	Yes

5.4 Design Expertise and Ways of Experiencing Uncertainty

Because this study focuses on decisions in design, it is appropriate to compare this new model of design in Table 5.4.1 with established models of design expertise as shown in Table 2.4.1 as part of the validation of the new model. While phenomenography demands the bracketing of one's own understanding of the phenomenon, including the bracketing of results from other literature, during analysis of the transcripts (Ashworth & Lucas, 1998), it is desired for validity purposes to triangulate new results with other published results.

Category 2 – Plastic correlates with Dreyfus' Novice level of expertise in the aspect of following strict rules, where Category 2 – Plastic engineers follow procedures and they deem their work is complete at the end of the checklist. By default, then, the Category 1 – Brittle engineer may be equivalent to the Naïve level of expertise, where Ross and Philip described having one choice or another, and either seemed to be good enough, so they picked one because of their relative familiarity with the selection.

There is a close comparison of Category 3 – Tolerant engineers and Competent level of expertise because of the aspect of trial-and-error, which in Category 3 is an experimental attitude. The Competent level of expertise shows an emotional attachment, which is similar to a Category 3 engineer having a deep sense of responsibility as a growing Subject Matter Expert and/or system owner.

Category 4 – Robust engineers, like Proficient level of expertise, seek reasons or evidence to justify a decision and can quickly set up well-coordinated plans to execute their decisions. But there is also a layer in Robust engineers of Expert level of expertise, especially in the matter of intuition. So, it seems appropriate to blend a Proficient and Expert level of expertise with Category 4 - Robust engineers. Lawson and Dorst (2009) point out that many professionals do not progress beyond Expert Level.

Category 5 – Resilient engineers have Expert and Master behaviors of reflecting on successes and failures and having an acute sense of context as it affects the design. It is the analogy of resilient materials being able to recover quickly that names the categories, and the matter of dwelling on success and failure is closely linked to recovering quickly. For Category 2 and above, failure is a teacher instead of a fright.

Table 5.4.1 Categories of experiencing uncertainty in design decisions compared to the Dreyfus model of expertise in design.

Level of Expertise	Approach to Design Practice	Approach to Design Practice Description	Category of Experiencing Uncertainty
Naïve	Choice based		Brittle
Novice	Convention based	Consider objective features of situation, follow strict rules	Plastic
Advanced Beginner	Situation based	Situational aspects important, sensitivity to exceptions to 'hard rules'	
Competent	Strategy based	Emotional attachment, trial-and-error, learning and reflecting, selects relevant elements, makes plan	Tolerant

Table 5.4.1 continued.

(Proficient)		Immediately see most important issues, appropriate plan, reasons what to do	Robust
Expert	Experience based	Respond intuitively, perform appropriate action straightaway	Resilient
Master	Create new schemata	Dwell on success and failure, acute sense of context, openness to subtle cues	
Visionary	Redefine field	New ways of doing things, new definitions of the issues, operating on margins of domain, paying attention to other domains	

CHAPTER 6. IMPLICATIONS AND CONCLUSIONS

One of the key implications of this outcome space and its summary is that designers in aerospace engineering rely on their peers as their primary strategy for managing uncertainty. The participants acknowledge formalized tools such as software packages and design and planning methodologies and of course engineering fundamentals and analysis. These technical aspects are the core of an engineer and they are very important within an engineering curriculum. However, it is significant that the ability to work across teams and an appreciation for the work of others is related to the advancement of the categories and the participants' ability to manage ever increasing uncertainty. The study was not probing teamwork in the research questions nor did the protocol explicitly probe this area but it emerged from the data analysis. As noted earlier the outcomes space has empty areas. An approach that guided students down one axis emphasizing the technical aspects solely with a plan to add teamwork later appears to be counter to how the engineers develop and would therefore have limits on its effectiveness. It would be more effective if these were linked with activities involving teams when they are learning how to handle design challenges with uncertainty.

The participants with significant responsibilities in industry (senior program managers, directors, and above) have described teamwork as the foremost strategy and have integrated it with their technical decision making. If the undergraduate curriculum seeks to prepare students to enter this environment, an integrated approach appears more effective. Because this outcome space shows a progression, it is recommended that students are not just put into teams in a design class, such as capstone design. Rather they should have multiple experiences where they can revisit teamwork and uncertainty in several progressively more challenging classroom experiences rather than to be confronted with one capstone design experience, as recommended by Grinter (1955). This is not to say that the traditional engineering disciplines have stagnated in the 1950s; on the contrary, efforts continue to update the engineering curriculum (Clough & et al., 2004). Rather, this work provides a focused lens on what development of the skill of managing uncertainty may look like as a comparison point for curriculum developers to assess their programs.

The higher category participants had learned how to respect and verify to their satisfaction the work of others. If teams were introduced early in traditional design teams of say four students, basic teaming skills could be taught. As students progress through their curriculum, more complex problems could be given to students where they are expected to work across teams in systems of teams. These experiences in a classroom where they can be processed by a mentoring faculty member would allow students the opportunity to progress in the model developed in this study.

6.1 For Educators

In order to be valuable in the aerospace engineering business, an engineer must be proficient in teaming and in designing complex systems. The engineer must also have a grip on their own personal feelings, which is not to be devoid of feeling, but to recognize that feelings could hinder their progress, whether it is related to how they feel about their teammates or how they feel about the scale of complexity of the design. The complexity and scale of Large Scale Complex Engineered Systems is insurmountable for an individual engineer, but can only be controlled by a team of "the right people with the right information at the right time", like Peter remarked.

As several participants indicated, they discovered the perspective of failure as a teachable moment rather than a fearsome event. It is this coping strategy among several that child development researchers describe as "resilient" (Luthar, Cicchetti, & Becker, 2000). In this study, some Robust and Resilient engineers note the unfortunate demise of younger engineers who could not overcome their fears and grow their understanding of the business. As Malcolm said: "They're not going to be looking at you and blaming you because it occurred… you're measured on how you react and how you handle them."

So, aerospace engineering education curricula need to provide multiple learning opportunities, including design, of reasonable complexity and personal investment that the student has opportunity to encounter these types of uncertainty and face their own fears. The instructor, with the knowledge of a growth in emotional responses, can be better equipped to coach students through this growth, knowing that there will be uncomfortable feelings for a while. At the same time, the design environment needs teammates (Smith, Sheppard, Johnson, & Johnson, 2005), mentors, maintainers or mechanics (a notable experience for the majority of participants), and customers. There is evidence that these experiences do not have to involve an aerospace application to develop these skills and can include activities such as community-engaged learning and service-learning (J. Huff, Zoltowski, Oakes, & Adams; J. L. Huff, Zoltowski, & Oakes, 2014).

From this study and others, educators can develop authentic design tasks for the classroom, within senior design as well as several semesters before, isolating and amplifying critical elements for students to develop "patterns of recognition", like Joel remarked. Authentic tasks have key characteristics: 1) realistically contextualized; 2) require judgment and innovation; 3) ask student to "do" the subject; 4) replicate key challenging situations in which professionals are truly "tested" in their field; 5) assess student's ability to use a repertoire of knowledge and skill; and 6) allow opportunities to rehearse, practice, and get feedback (Hansen, 2011). This study in particular uncovered some of that repertoire of knowledge and skill, particularly managing uncertainty in design decisions with teammates and stakeholders.

This study and others confirm that teaming in class projects needs to be strategically organized and that the students need to be aware of and participating in team construction, whether in an aerospace-centric course or in another design course. Several examples of design projects throughout the undergraduate curriculum have been developed, assessed, and disseminated. Aircraft design has been implemented at the sophomore level (R. M. Cummings & Hall, 2005). Project-based service learning in EPICS (Coyle, Jamieson, & Oakes, 2005) is a design course that could be leveraged over several semesters. EPICS is particularly attractive because the students who return for multiple semesters are expected to take on more leadership roles, and, by extension, would have more exposure to more forms of uncertainty. The Learning Factory (Lamancusa, Zayas, Soyster, Morell, & Jorgensen, 2008) is another prize-winning concept of multidisciplinary teaming design projects. Completely re-envisioned design-centric programs include Iron Range Engineering in Minnesota and Olin College in Franklin, Massachusetts. If laboratory-based design courses are unsustainable for administrators, then design projects in typical underclassmen engineering science courses like statics (Atadero, Rambo-Hernandez, & Balgopal, 2015) can be employed.

In any case, the overarching goal is to get students comfortable interacting as teams and with other teams in a larger system. In this way, they can become proficient in Systems Thinking in advance of industrial work that deals with Systems-of-Systems. Educators may find certain itemized behaviors and tasks in Table 2.3.1 that can be implemented or re-emphasized as part of project-based learning (Barron et al., 1998; Bielefeldt, Paterson, & Swan, 2010; Dym et al., 2005) environments.

Because I am advocating the changing of education systems, some examination of instructors as part of an academic complex system is necessary. An instructor may have the view of classes as individual systems that the instructor "owns" or has responsibility and authority for that class. But, one class affects another class, the most obvious example of that being prerequisite classes. So, it would be more effective for instructors to have a least a Tolerant perspective on uncertainty, where a person has a deep conceptual understanding of the system (class) and a sense of ownership, but also that the boundaries between classes are negotiable for the sake of the performance of the entire complex system. In other words, the boundaries between classes refers to the content, where a design project in a heat transfer class may be of similar content to the prerequisite thermodynamics class' design project, but with increased complexity. In order to negotiate well, instructors need to have some sense of teamwork.

The second aspect of students having an awareness of their personal response to uncertainty may be uncovered and explored through reflective writing (Kalman, 2007; Schön, 1983). Reflective thinking enhances learning and a student may self-identify areas for improvement. Based on the vertical dimension of the outcome space, and especially the depth of reflection from the Robust and Resilient participants in Sections 4.3.4.4 and 4.3.5.4, an instructor may pose reflection questions to students about uncertainty, such as those primary questions I asked in the interviews:

- Were there things in this design experience that you did not know?
- Where was there uncertainty?
- How was the uncertainty treated?
- How did the uncertainty affect the decisions you made about the design?
- Did you learn anything about uncertainty in design from your experience?

6.2 For Future Research

Future research questions first posed in Section 2.8 are revisited here. Skill Theory, first shown in Section 2.6 in Figure 2.6.1 and Table 2.6.1, can assist in a logical and hierarchically related set of tasks and skills discovered in this study. Revisiting the theory, a learner intercoordinates sets of skills into a higher level skill, which is induced by the environment and the task. This will be a significant addition to content, assessment, and pedagogy of the higher level skills of managing uncertainty, making decisions, designing, and teaming. With the content and tasks defined, then the assessment schemes for those tasks should be developed with ease and assurance of relevance. The pedagogy follows that the teams of students should be allotted time to accomplish their design tasks and that the teams of students should be encouraged and coached to seek feedback from mentors and customers.

From each of the categories, key skills and tasks can be identified as a first step in developing new and improved curricula. Since the outcome space of this study is hierarchical, it follows that a hierarchy or progression of skills learned can be extracted from the outcome space. A progression of skills through each of the categories should be apparent. This preliminary description can serve as a starting point for future research on appropriate classroom interventions for managing uncertainty in design decisions.

In Category 1 – Brittle, the participants indicated that they were still learning to 1) solicit feedback informally; 2) to become more information-literate; and 3) to model the different engineering phenomena they were assigned to contribute to the design. In each of these developing skills, epistemic uncertainty is a subset.

In Category 2 – Plastic, the participants indicated that they were still learning to 1) solicit feedback from mentors; 2) justify decisions to themselves first and then present to others; 3) validate and verify models of engineering phenomena; and 4) manage a schedule and budget for their project. In each of these developing skills, epistemic uncertainty is a subset. This category of participants appears to have attained the skill of soliciting peer feedback, and are compounding or substituting mentor feedback now. These participants appear to have increased their proficiency in information literacy, and are now intercoordinating information literacy with modeling knowledge to create validation and verification schemes. Simultaneously, they are intercoordinating information literacy and feedback from peers and mentors to develop the skill of justifying decisions. Though schedule and budget representations are a lower level skill, it seems that the participants did not intercoordinate schedule and budget with design until they were required by the task, just as Skill Theory predicts.

In Category 3 – Tolerant, participants have developed the skills of 1) deep conceptual understanding of a particular phenomenon or system; 2) valid experiment design; 3) reframing phenomena as trade-offs and risks; and 4) tempering one's personal response to uncertainty. In this category, participants have intercoordinated feedback from mentors and justification of decisions to develop deep conceptual understanding. They have compounded justification of decisions with valid experiments, schedule and budget, trade-offs and risks, to develop a mental model (Lehrer & Schauble, 2000; Magnani, 1999) of a whole system. Mentors and peers are also part of the mental model of a system, especially where a peer "owns" another interacting system. In these skills, aleatory, ambiguity, and epistemic forms of uncertainty are subsets. Trade-offs could have ambiguous choices and outcomes. Viewing aleatory uncertainty as risk allows an engineer to manage risk instead of attempt to eliminate or reduce uncertainty.

In Category 4 – Robust, participants have developed their mental models of systems further to master 1) systems of systems thinking and 2) develop new methods, processes, and solutions. Understanding a person as a customer is a lower level skill, but differentiating customer feedback from peer and mentor feedback is a skill more apparent in this category. Participants here have compounded their understanding of customer feedback with their understanding of systems-of-systems in order to develop a robust design. Participants here also see peers and subordinates as "owners" of a system as part of their mental model, and they see uncertainty in interaction between these systems. Participants here also have mastered the skill of experiments, deep conceptual understanding, risks, and trade-offs, in order to develop and implement new methods and solutions. In these skills, uncertainty in developing new methods is phenomenological epistemic uncertainty, which can be reduced when the method is implemented. Uncertainty with the customer can take the form of behavioral, ambiguous, and/or interaction. In this category, the quantity and quality of uncertainty are increasing compared to the lower categories.

In Category 5 – Resilient, participants have developed the skills of 1) building trust and a sense of "collective" in teaming; 2) delegating tasks and responsibilities; 3) tempering one's personal response to others' uncertainties; and 4) investigating and understanding the customer's needs and feedback within a larger context. In this category, interaction uncertainty is a subset of teaming and understanding the customer. There are also all the other forms of uncertainty that Category 4 engineers experience.

A second branch of research could expand this work with different populations and different contexts. For example, the same study could be conducted with underclassmen undergraduates to discover progress made in managing uncertainty over the typical four to five years of study. Also, the same study could be conducted within a single aerospace company, or in a non-aerospace engineering industry. Would the results presented here be replicated, or would there be other strategies for managing uncertainty discovered in other contexts? If so, how would the new results be applicable to the undergraduate curriculum?

A third branch of study, stemming from the unexpected results here, is to examine teams of teams, in order to corroborate the participants' perceptions of teamwork with researchers' observations of teams of teams in action. A different research methodology might be employed here to study groups instead of studying individuals. This branch of research questions aligns with Deshmukh and Collopy's (2010) questions about organizations and teams: "how does the adaptability of an engineering design organization impact the large complex systems it develops? … what attributes of a design team must be expressed in a useful and rigorous model of design team behavior?" Perhaps the expert team behavior models I showed in Table 5.3.1 partially answer their second research question.

6.3 Conclusions

Managing uncertainty in design decisions has been shown in this study to be an acquired skill, not just an innate or unteachable skill. This skill is a system of connected lower level skills, and increasing connections between lower level skills indicates a path of development that allows for teaching these skills within a student's *zone of proximal development* (Vygotsky, 1986). At first, a student developing a skill will mimic or imitate an instructor or mentor, but given multiple tasks where a student focuses on certain content moment by moment, and given assessments that can also serve as a cycle of learning, a student will gradually develop the higher level skills being sought (Fischer, 1980). This study has shown that it could be years of gradual development for a skill in the workplace.

The major contribution of this study is the uncovering of the key elements in varying levels of awareness of uncertainty in design decisions that allows for future work in developing learning simulations and interventions for the undergraduate curriculum. While the context of this study was specifically the aerospace engineering because of the industries' commitments to safety and to expanding the boundaries of knowledge, the elements of the skills here are applicable to other engineering disciplines engaged in design of complex systems. The discoveries in this study of key behaviors and cognition will ultimately assist educators in better preparing the next generation of engineering leaders in aerospace and students who will help solve the world's Grand Challenges ("Introduction to the Grand Challenges for Engineering," 2013).

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APPENDICES

Appendix A Informed Consent and Recruiting

IRB approved the study with Dr. William Oakes as the primary investigator under Exemption 45 CFR 46.101(b)(2) (U.S. Department of Health and Human Services, Sep 24, 2004). The study here is human research, governed by 45 CFR part 46. The research involves the use of interview procedures only. The research does not involve children. The final condition "is the information obtained recorded in such a manner that human subjects can be identified, directly or through identifiers linked to the subjects; and could any disclosure of the human subjects' responses outside the research reasonably place the subjects at risk of criminal or civil liability or be damaging to the subjects' financial standing, employability, or reputation?" is not met, thereby exempting the research from 45 CFR part 46 requirements. The subjects are not being placed at risk because they are simply being asked about their professional experience, a matter of common knowledge within their employing companies.

Required forms for IRB under these conditions are:

- Exemption 2-3 Form v1-13

Optional forms for IRB under these conditions are:

- Participant Information Sheet
- Recruiting email

The Purdue University Human Research Protection Program Institutional Review Board granted my exemption request on Nov 25, 2014. The exemption document includes a requirement "when human subjects research will be conducted in schools or places of business, investigators must obtain written permission from an appropriate authority within the organization. If the written permission was not submitted with the study application at the time of IRB review… the investigator must submit written permission to the IRB prior to engaging in the research activities". Data was collected after the participants' regular work hours when they were in the comfort of their own homes.

Secondly, IRB has two rules for recruiting students. To meet those requirements, students were emailed instead of using classtime to announce recruiting efforts, a cash incentive was offered instead of offering any sort of class credit, and the confidentiality of the students was maintained just like other participants by not informing their instructor about any students' responses or participation. The rules specifically are:

1. To recruit from Purdue University classrooms, the instructor and all others associated with conduct of the course (e.g., teaching assistants) must not be present during announcement of the research opportunity or any recruitment activity. This may be accomplished by announcing, in advance, that class will either start later than usual or end earlier than usual so this activity may occur. It should be emphasized that attendance at the announcement and recruitment are voluntary and the student's attendance and enrollment decision will not be shared with those administering the course.
2. If students earn extra credit towards their course grade through participation in a research project conducted by someone other than the course instructor(s), such as in the example above, the students participation should only be shared with the course instructor(s) at the end of the semester. Additionally, instructors who allow extra

credit to be earned through participation in research must also provide an opportunity for students to earn comparable extra credit through a non-research activity requiring an amount of time and effort comparable to the research option.

Recruiting Email:

[Potential participant's name],

You are receiving this email you have been identified as a good designer and a good decision-maker. We are recruiting participants for a research study on how aerospace engineers manage uncertainty when making design decisions. The information you provide will be used to inform the undergraduate engineering curriculum to improve students' awareness of uncertainty in design and decision-making processes. The data you provide by your participating in this study will increase the effectiveness of undergraduate education, especially making new graduates more prepared for the professional, competitive, high-stakes workforce that you are currently employed in.

The study will consist of an interview over Skype (or other video chat service) for no more than 2 hours. Questions will focus only on your educational background and your design experiences. You will have an opportunity after the interview to check and edit the information that you provided before we include it in any analysis.

For your peace of mind, please know that there is absolutely no obligation for you to participate in this study. In future publications from this study, there will be no identifying information about you, your employer/school, or the projects you have worked on. No proprietary or confidential company information will be revealed in publications from this study. No one, including your employer/professors, will know that you participated in this study.

If you are interested in participating, please email Toni at cumming3@purdue.edu for further information or to set up an appointment. Alternatively, you may contact the sponsor of this research, Dr William Oakes, at oakes@purdue.edu.

Thanks,

Antonette (Toni) Cummings, P.E.

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PhD Candidate, Engineering Education

There were some modifications to recruit senior design aerospace engineering students, including compensation of $15 for their time. The first two paragraphs of the email above have been modified (changes emphasized in italics):

You are receiving this email because *you have been identified as an aerospace engineering student with design experience*. We are recruiting participants for a research study on how aerospace engineers manage uncertainty when making design decisions. The information you provide will be used to inform the undergraduate engineering curriculum to improve students' awareness of uncertainty in design and decision-making processes. The data you provide by your participating in this study will increase the effectiveness of undergraduate education, *especially making new graduates more prepared for the professional, competitive, high-stakes workforce.*

The study will consist of an interview over Skype (or other video chat service) for no more than 2 hours. Questions will focus only on your educational background and your design experiences. You will have an opportunity after the interview to check and edit the information that you provided before we include it in any analysis. *You will be compensated $15 for your participation.*

As a side note, when a reminder email was sent to the recruits, a more casual tone was used, saying, "Hi! Just following up with the email I sent you two weeks ago. Am hoping you can help me. I'm interviewing people who have done aerospace engineering design work for my dissertation. Do you have about an hour in the next two weeks that we could talk? I would very much appreciate it. I completely understand if an interview is not possible, but I hope to hear from you!" At least two of my personal said that the first email sounded like spam email to them and that is why they did not respond to the first email. Even though many of the initial recruits were friends, the first recruiting email volley did not sound personal enough to merit a response.

Appendix B Interview Protocol

Thanks for agreeing to be interviewed. Before we start, I want you to know that your participation is entirely voluntary and you can stop at any time for any reason. You should not feel obligated in any way to participate. I will not reveal to anyone that you did or did not complete the interview. Are you still comfortable participating?

I will make every effort to make your interview anonymous and unidentifiable in published papers. I will de-identify you, your company, and your projects/products. I will also provide you the opportunity to check and edit the conversation afterwards. I will only include what you are comfortable including.

You have been identified by your peers as a good engineering designer and decision-maker. The purpose of this study is to understand how you deal with uncertainty as it arises in design and decision-making in your career. From there, we hope to use the results of this study to inform the undergraduate curriculum to help students become better decision-makers earlier in their careers.

First, let me ask you about you.

Interviewee Background Information

- What is your education background?
- What engineering positions have you held with other companies before this one?
- What department/unit/section are you employed in now?
- How long have you worked as an engineer for this company?
- What is your current job title?

- What is your current range of responsibilities?

Company Background Information

- What kind of company, agency, or organization do you work for? (private industry, state agency, federal agency, military)
- How many employees are in your department? Location?
- How many other professional, technicians, or other employees are in your department, section/unit?
- Who are suppliers to your company?
- To whom does your company supply products and services?

Primary questions on decision-making in design

- Can you tell me about a time when you had to make a decision on a design?
- What did that experience involve?
    - *What was the goal?*
    - *What were you designing?*
    - *Who were you designing it for?*
    - *Where were you designing?*
    - *Who else was involved in the design experience?*
    - *What was your specific role in the experience? What were your responsibilities?*
- What were the decisions that needed to be made in the design?
- What was your process for making those decisions?

- How did you go about determining possible solutions? What methods of analysis were used?
- How did you represent the design?
  - *Formulae*
  - *Prototypes*
  - *Model*
  - *Functional description*
- What criteria were used to determine the best decision/solution?
- How well received were the solutions/decisions?
- To what degree have the solutions/decisions been implemented?

Primary Questions on Experiencing Uncertainty

- Were there things in this design experience that you did not know?
- Where was there uncertainty?
- How was the uncertainty treated?
- How did the uncertainty affect the decisions you made about the design?
- Did you learn anything about uncertainty in design from your experience?

Word choices

- Could you tell me what it means to you when you use the word "uncertainty"?
- Is there another word or phrase that you would use that describes uncertainty in your field?
  - *Uncertainty that is reducible if you gain more knowledge*
    - *Models*

        - *Human or organization behaviors*
        - *Natural phenomena*
    - *Uncertainty that cannot be reduced, even with more knowledge*
    - *Ambiguity in word choices and vocabulary*
    - *Interactions of organizations*
- What formal training do you have in uncertainty?

Primary questions on learning about uncertainty

- Can you tell me about previous experience from similar or dissimilar tasks that affected your decision-making?
- How do you think this is different from the experience we talked about earlier?
- Did you approach the project in the same way as your approached the previous one we just discussed?
- What experiences do you believe contributed the most to your understanding of uncertainty in design decisions?
- What advice would you give to undergraduate students about uncertainty in design decisions?

Closing questions

- Anything that you want to add about your experiences with uncertainty in design decisions that we haven't discussed yet?
- Any questions for me?

Appendix C Iterations of Analysis

The steps are listed below, having been documented in a research notebook and replicated in an nVivo 10 project.

1. Moments after each interview, I memoed my thoughts in my research notebook, typically one page of handwritten notes.
2. After receiving a transcript of an interview from a third party service, I listened to the audio recording and corrected the transcript.
3. I de-identified each transcript, removing university names, business names, and project or aircraft names. Listening to the audio and de-identifying the transcripts is the first cycle of familiarizing myself with the data.
4. Each participant received a de-identified transcript for a member check. I declared that I would respect and include any and all edits they wanted to make. I asked for any edits to be returned to me within two weeks. I also promised to return the results of my study to the participants as to avoid the researcher's "seduction and abandonment" (National Commission for the Proptection of Human Subjects of Biomedical and Behavioral Research, 1978).
5. As I approached 20 interviews completed, I thought I was beginning to hear the same sentiments from new participants. However, I did not have enough females or enough voices from subsystem companies, so I continued to recruit.
6. When I completed 25 interviews, I was reasonably certain that I reached saturation after I had gained more female voices and subsystem voices.

7. As Iteration 2 of familiarizing myself with the data, I printed and read 3 transcripts per day, noting decisions, design, and uncertainty quotes on notecards. I grouped the notecards by these topics without regard to the clustering of participants. Purple notes were design topics; yellow notes were decision topics; orange notes were uncertainty topics. Left side was before creating categories; right side is after.

Iteration 2 – 2015 08 02

Figure C.1 Iteration 2 of creating categories.

Categories

- Fear and frustration – need external motivation
    - Margaret, Edmund, Silvia, Miranda, Viola, Philip, Luciana

- Ignorance or uncertainty of technical phenomena and analysis tools
    - Silvia, Ross, Viola, Miranda, Diana
- Rely on historical data, what has been done before
    - Diana, Vincent, Oliver, Curtis, Ross, Ronald, Bertram
- Base on fundamental principles
    - Bernard, Abraham, Viola
- Measure risk
    - Stephen, Abraham, Alonso, Curtis, Malcolm
- Have contingency or back-up plans
    - Joel, Edmund, Jacques, Malcolm, Stephen
- Rely on more experienced engineers
    - Viola, Nathaniel, Bertram, Bernard, Edmund, Frank, Duncan, Vincent, Diana, Jacques
- Optimization
    - Nathaniel, Silvia, Vincent, Luciana
- Cycles and trends
    - Abraham, Peter, Stephen, Curtis
- Repeatability in experiments
    - Frank, Oliver, Miranda, Stephen, Edmund, Ronald
- Demand evidence now
    - Joel, Curtis, Alonso, Oliver, Jacques

Common themes

- Intuition is developed from experience
- Iteration occurs with internal and external customers
- Teamwork helps find distributed expertise
- Teamwork helps review the design for missing work or errors
- Proof of concept is desired
- Evidence can be a Subject Matter Expert opinion or it can be written and measured data
- Everybody wants to do a good job

8. I copied these quotes into nVivo per participant, making it easier to move whole transcripts into or out of categories.
9. I kept notes of my dreams where categories seemed to coalesce and make memories (Blakeslee, 2000).

Iteration 3 – 2015 08 04

Categories

- Ignorance – will the technology work? Fear and anxiety; External motivation
- Trial and error
- Single cycle – diminishing returns for iteration

- Repeatability and consistency – experiments, standardization, provide evidence; technology does indeed work and I can prove it
- Cycles or trends – temporal, schedule, cost; technology will work, just need to get it at the right time

Common themes

- Emotional component
- Recent events → spotlight memories or Law of Recency?

10. I continued to memo my thoughts as I read quotes in nVivo.
11. I moved back and forth between 20” x 30” paper spaces and nVivo, grouping printed sheets of quotes and electronic quotes. I was able to share printed notes with another researcher familiar with aerospace and phenomenography.

Iteration 4 – 2015 08 06

Categories – Forms of Uncertainty

- Looking forward (outcomes)
- At start line
    - Who to ask
    - What to ask
    - What path to take
- Looking backward (do not know that something exists)

- Looking sideways (simultaneous)
- Looking upstairs (decisions in a business hierarchy)
- Controllable and uncontrollable (Robust Design ideas)
    - Controllable uncertainties require evidence and repeatability
    - Uncontrollable uncertainties require intuition and judgment from prior experience
- Republican mindset
    - Rumsfeld: known knowns, known unknowns, unknown unknowns
    - Reagan: trust and verify

Categories – Management Strategies

- Assume
- Ignore
- Break into smaller pieces (but not a systems thinking view)
- Due diligence (personal, individual)
    - Calculations, analysis tools
    - Prior documentation by others
- Informal peer review
    - Solicit many opinions
    - Decide which ones are valid (an emotional decision)
- Formal review board, direct supervisor as your spokesperson
    - Systems view of the design problem
- Tools for decision-making like 6 Sigma are rare

- Subject Matter Expert opinion
- Direct hierarchy opinion or decision (HIPPO = highest paid person's opinion)
- Margins, boundaries, conservatism

Categories of Key Learning Experiences or Interventions

- Design projects in school – mandatory
- Design projects outside of school – voluntary
- Internships – responsibility and consequences
- Failures – aircraft loss, loss of life
- Going to factory and talking with mechanics – having to build something
- Mentors
- Home grown decision-making simulations and courses
    - Project management courses, university sponsored
    - 6 sigma courses

Common Themes

- Flight safety
- Due diligence, including peer review
- Cost
- Schedule
- Teamwork
- Evidence

- Communication

Iteration 5 – 2015 08 07

Category 1 – Bertram, Luciana, Margaret, Silvia

There are answers (technical solutions) for somebody else prior. Reliance on external confirmation of decisions. Reliance on patterns of previous successful projects from others. Ignorant of product history of a private company.

Category 2 – Bernard, Diana, Edmund, Miranda, Philip, Ross, Vincent

Some demonstration of personal ability and previous knowledge. Apply personal due diligence. In a new task, transfer some skills and develop new skills. While developing new skills, they are unsure if there is an answer or solution.

Category 3 – Abraham, Nathaniel, Stephen, Viola

There is an answer or a solution; it is a compromise of technical parameters. Includes more parameters than Category2. Not yet including users' larger context.

Category 4 – Curtis, Frank, Jacques, Oliver, Ronald

Seeking repeatability of results, which implies rigorous testing and good planning ahead of test. Consideration of applying margin or conservatism on top of repeatable results. Technical answer or solution definitely exists.

Category 5 – Alonso, Duncan, Malcolm

Company wide systems view of teams solving problems. Relying on "intuition" as developed by much personal experience.

Category 6 – Joel, Peter

Customers' larger context and priorities considered. Identifying controllable versus uncontrollable factors. Relying on evidence, not intuition: what information, what person, what fidelity.

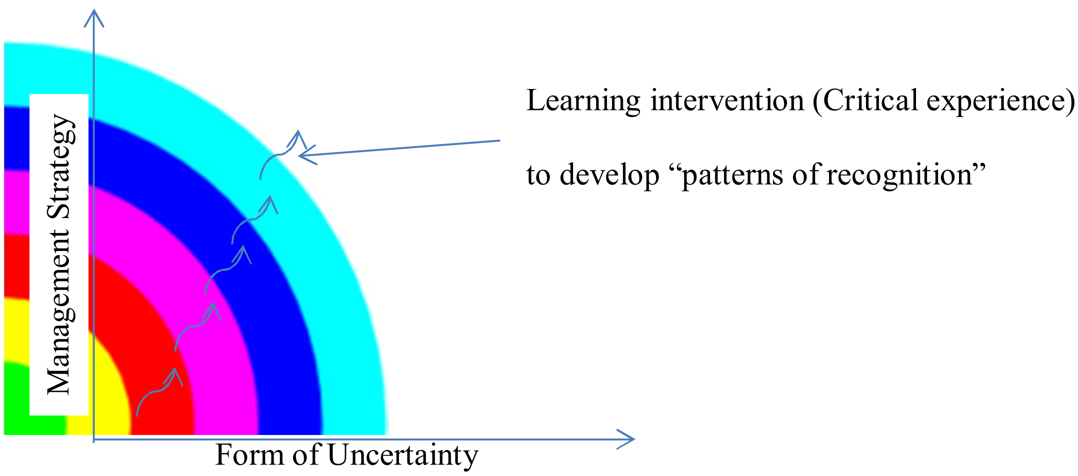

Figure C.2 Iteration 5 possible outcome space graphic.

Iteration 6 – 2015 08 17

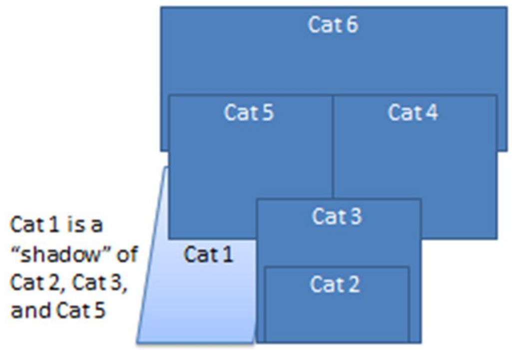

Figure C.3 Iteration 6 hierarchical outcome space.

Table C.1 Iteration 6 category description.

	Task	strategy	Uncertainty
6	External customers first	Controllable evidence needs "right" person, "right" fidelity; uncontrollable factors have "intuition" applied	Uncontrollable market trends, cycles
5	Program management	Early and broad coordination; "intuition" from experience; systems view	"right" level of task ownership
4	Flight test, safety-critical	Find biggest factors Stop and examine trends Examine all factors simultaneously first	Margins and conservatism on repeatable results
3	System conceptual design	Invite criticism Re-use existing technology Underlying principles Start from known	Answer or solution is some compromise
2	Accountability for schedule and budget	Peer review Due diligence – break into smaller pieces, justify to self first	Unsure if technical solution exists
1	Individual project, conceptual design	External decision makers Explicit decision tools Guess and check	Answers in someone else's prior efforts

12. In Iteration 7, I reviewed the transcripts again just for emotions and created categories.

Iteration 7 – 2015 09 06

Categories of Emotion

1. Will it work – Philip, Ross, Silvia
    a. Participants are unsure if their designs will perform to the specifications. Punishment may follow a failed design. Participant makes choices of what work to do based on their prior knowledge that they have confidence in, or reject a task because of unfamiliarity. Not much sense of being responsible to a team. Needs some confirmation from management in order to be more confidence in their own ideas.
2. Managers Influence Intense Emotions – Edmund, Luciana, Margaret
    a. Emotions of participants correlate with their managers' involvement. Lack of external leadership leads to fear, low confidence, confusion, doubt, worry, lack of trust. Managers' encouragement is very much appreciated and is the motivator to make the next steps of the project succeed.
    b. Thrown Into the Deep End – Diana, Vincent
        i. New job or new product, unfamiliar with the rest of the product line, being given responsibility and accountability. Gain confidence after seeing onesself succeed with this first task/responsibility. Learning to coordinate with others.

3. Experimental Attitude – Curtis, Oliver, Stephen, Viola
    a. Participants have experienced some surprises in design. Participants have had a few panic moments within themselves or with their intended users. They have separated failure in design from failure in themselves. But they may have had previous design experiences where they felt guilty/responsible for a design failure. They have resolved to be better prepared and not to take things personally. They are getting better prepared by planning experiments logically and efficiently.
4. Managing Teammates' Emotions – Jacques, Joel, Miranda
    a. Decisions are difficult because they are primarily trying to overcome teammates' resistance to change or progress. Participants are trying to identify the right time to introduce the decisions and are particularly sensitive to their teammates' reactions. The participants here acknowledge that their own feelings get hurt when they feel that others are blaming them. Doubt and stress are palpable, but there is a likely positive outcome happening soon.
    b. Resolving Conflicts in Design – Abraham, Alonso, Bernard, Bertram, Nathaniel, Ronald
        i. Conflicts exist among physical parameters, such as forces, temperatures, materials, aircraft performance. These parameters may be "owned" by other departments or groups, so resolution of physical parameter trade-offs can be described as "making everybody happy". However, participants do not have a sense of

panic or a fear that the conflict will not be resolved. Some acknowledge their own bias towards their ideas and are willing to seek critique.

5. Over It Now – Duncan, Frank, Malcolm, Peter

    a. Participants have almost no intense or negative emotions as they make business-shifting decisions.

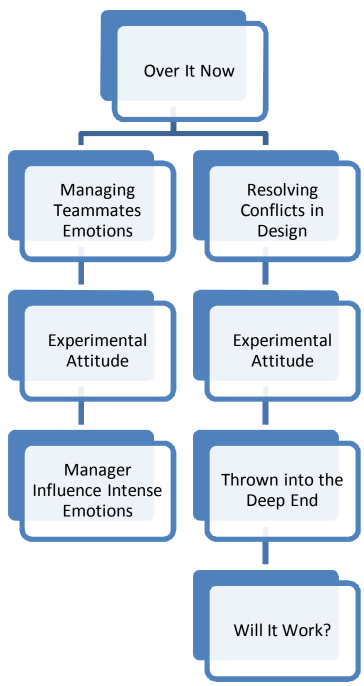

Figure C.4 Iteration 7 hierarchical outcome space.

13. I reviewed the transcripts again, attempting to bracket out the job-specific language the participants use to find the "essence" of their experience of uncertainty, regardless of the task they have been assigned.

14. I reviewed the emotion categories with another researcher. The other researcher suggested that an outcome space that moves up and/or to the right is the convention for “more comprehensive”.
15. In Iterations 8, 9, and 10, I reviewed the literature again, looking for vocabulary to describe categories in one or two words. Also, I completed a closer read of key works and their bibliographies, such as the Expertise Handbook (Ericsson, 2006) and the several scales for tolerance for ambiguity (Herman et al., 2010; MacDonald, 1970; McLain, 1993). I considered other literature of ambiguity, decision-making, and risk (Hollnagel, 2011; Lipshitz & Strauss, 1997; Philippo et al., 2013).

Iteration 8 – 2015 09 09

Another researcher suggested that I place two names together and describe the similarities and differences between them. Then I should take another name and describe the similarities and differences among the three, and place the names in some position relative to each other to express some measure of comprehensiveness of experience. I completed this exercise on paper. The second step was to draw groups around these names and to describe the groups. The result is in Figure C.5 below.

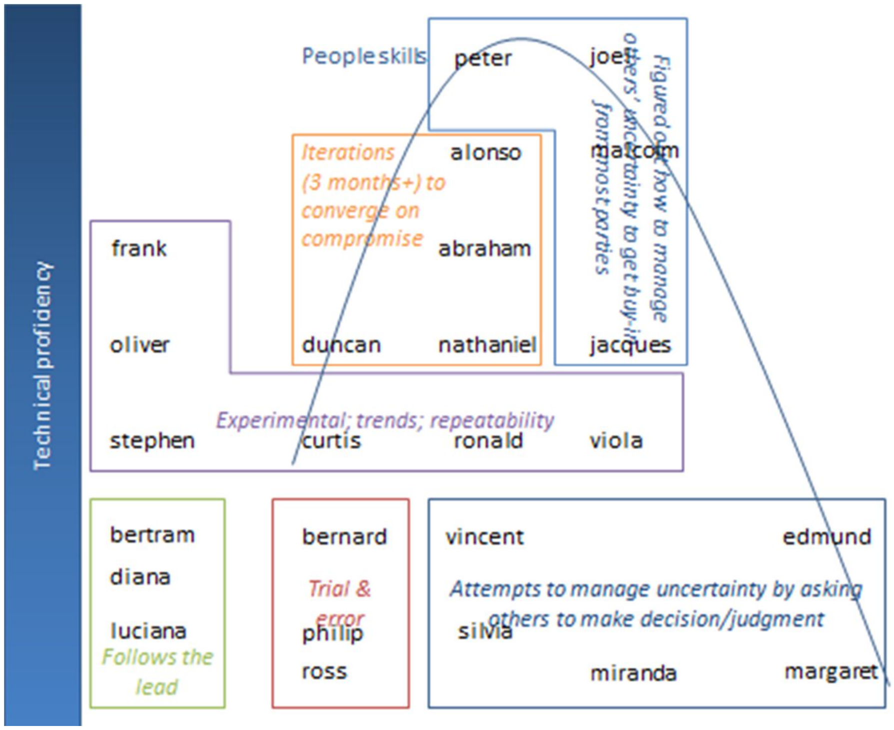

Figure C.5 Iteration 8 hierarchical outcome space.

I considered the nature of the design tasks that the participants described apart from their description of their experiences of uncertainty. I applied a framework of sensemaking (Daft & Lengel, 1986) in organizations to the participants to see if any patterns emerged in Figure C.6 below:

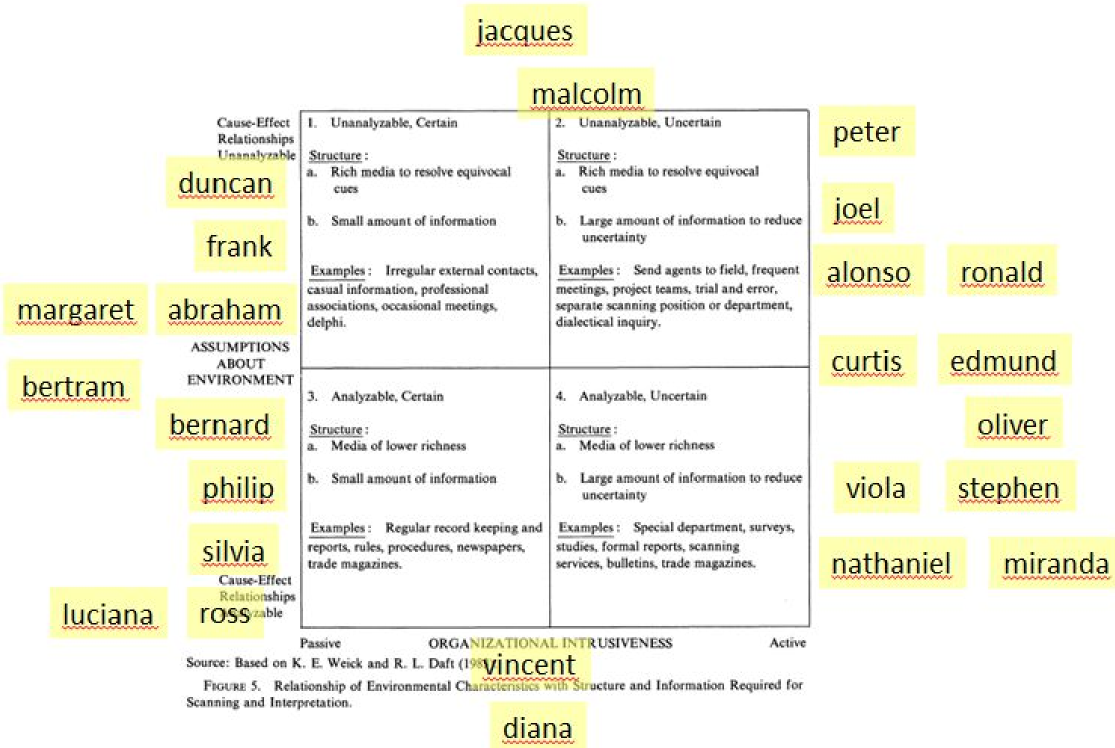

Figure C.6 Iteration 8 Daft (1986) organizational uncertainty.

Iteration 9 – 2015 09 11

An alternative is to consider the literature and see if groups emerge as a result of overlaying previously published literature on to the names above. I considered literature on coping mechanisms (Lipshitz & Strauss, 1997). I removed my groups and applied the codes from Lipshitz's table below into Figure C.7 below:

Table C.2 Reproduction of Lipshitz & Strauss (1997) tactics of coping with uncertainty.

Tactic	Definition
	Tactics of reduction
1. Collect additional information	Conduct an active search for factual information.
2. Delay action	Postpone decision-making or action taking until additional information clarifies the decision problem.

3. Solicit advice	Solicit advice/opinion of experts, superiors, friends or colleagues.
4. Follow SOPs, norms, etc.	Act according to formal and informal rules of conduct.
5. Assumption-based reasoning	Construct a mental model of the situation based on beliefs that are (1) constrained by (though going beyond) what is more firmly known, and (2) subject to retraction when and if they conflict with new evidence or with lines of reasoning supported by other assumptions.
	Tactics of acknowledgment
1. Preempting	Generate specific responses to possible negative outcomes.
2. Improve readiness	Develop a general capability to respond to unanticipated negative developments (e.g., put forces on the alert, leave some resources unused).
3. Avoid irreversible action	Prefer or develop reversible course of action, prepare contingencies.
4. Weighing pros & cons	Choose among alternatives in terms of potential gains and losses.
	Tactics of suppression
1. Ignore uncertainty	Act as if under certainty.
2. Rely on "intuition"	Use hunches, informed guesses, etc., without sufficient justification.
3. Take a gamble	"Take a chance," throw a coin, etc.

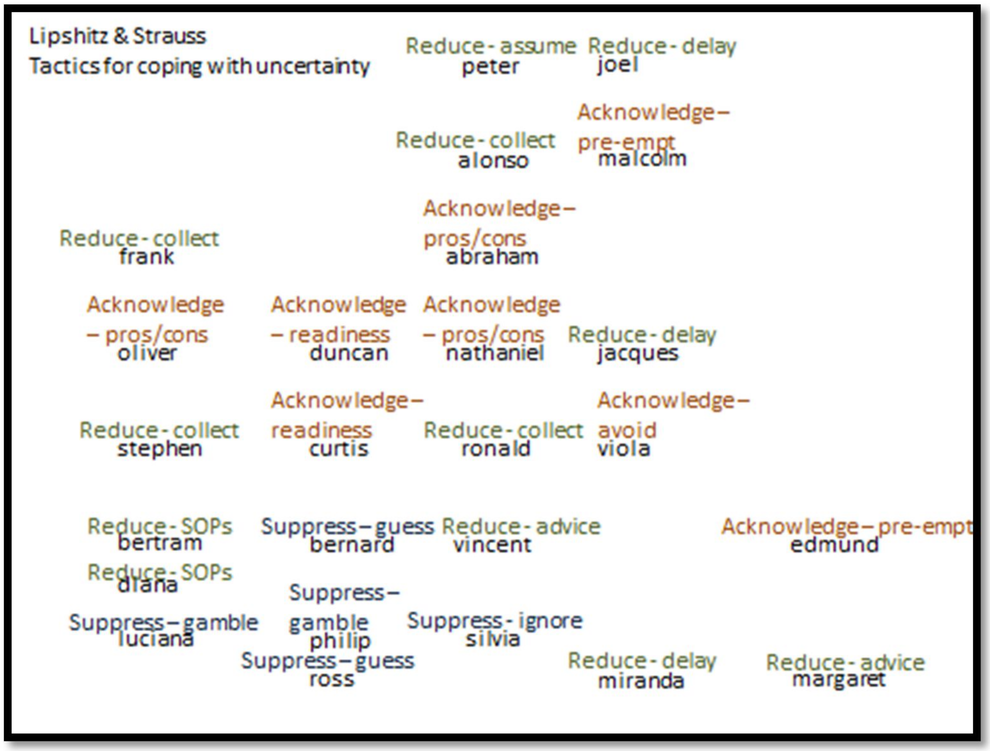

Figure C.7 Iteration 9 outcome space with Lipshitz's coping mechanisms applied.

Iteration 10 – 2015 09 16

A participant provided me a book chapter that she thought would be relevant to my study. I agreed it was relevant to talk about Resilient Engineering (Hollnagel, 2011). However, in the outcome space in Figure C.8 below, there appear to be a few outliers.

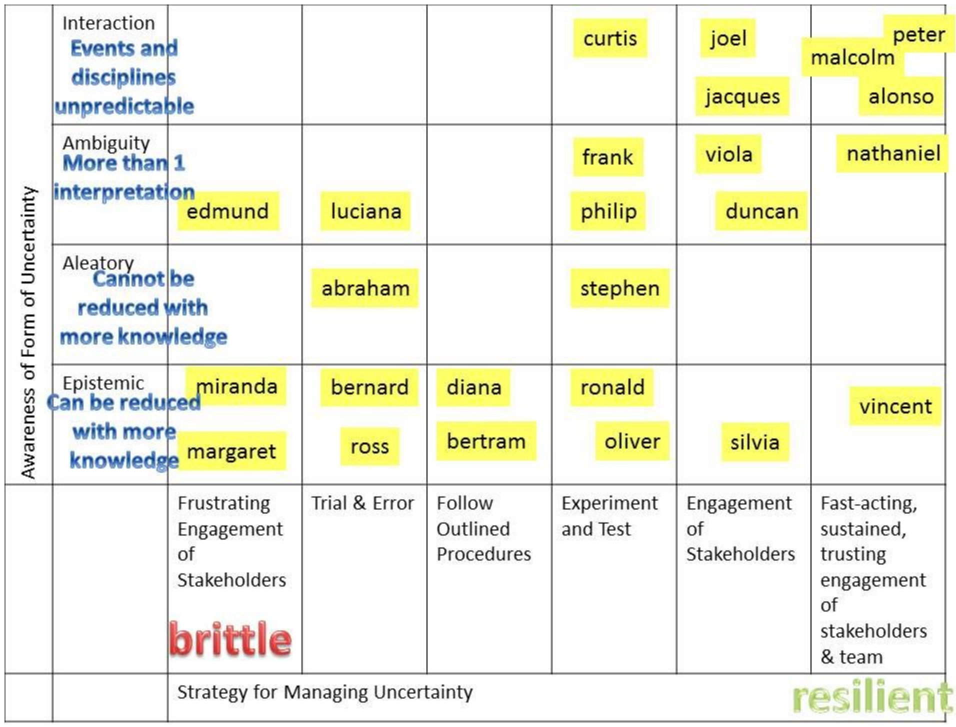

Figure C.8 Iteration 10 hierarchical outcome space.

Table C.3 Iteration 10 categories description.

Category	**Uncertainty Management Strategy**	**Emotional Responses**	**Design Tasks**
Brittle	Frustrating engagement of stakeholders	Managers‘ attitude highly influential on participants’ attitude	Design may not have much progress, depending on managers
Plastic	Trial and error	Emotions (confidence) tied to whether design works or not	Design makes progress when participant finds that something has worked

Classic	Follow defined procedures	Feels like "being thrown into the deep end", confidence from following someone else who has been successful	design makes progress because the checklist has been followed
Tolerant	Plan an experiment and test	Experimental attitude; accept that some things will not work	Design has some parallel efforts, some may terminate, and some sequential efforts; all is considered progress
Robust	Early engagement of stakeholders	Now having to manage other teammates' emotions; decisions feel personal	Designs may have short and long term solution packages
Resilient	Fast-acting, sustained, trusting engagement of stakeholders & team	Have gotten over the likely criticism and resistance to decisions.	Systems level design tasks must be parsed appropriately

16. Another researcher read several transcripts that I selected as having significant variation among them, one that I thought was an expert at managing uncertainty, mostly driven by a high-ranking job title, and one who specifically used a number of negative emotions throughout the transcript.
17. I went through four more rounds of category description and differences, expressed in paper and electronic formats. The fourth round mentioned here is the final result of this entire document.

Iteration 11 – 2015 09 18

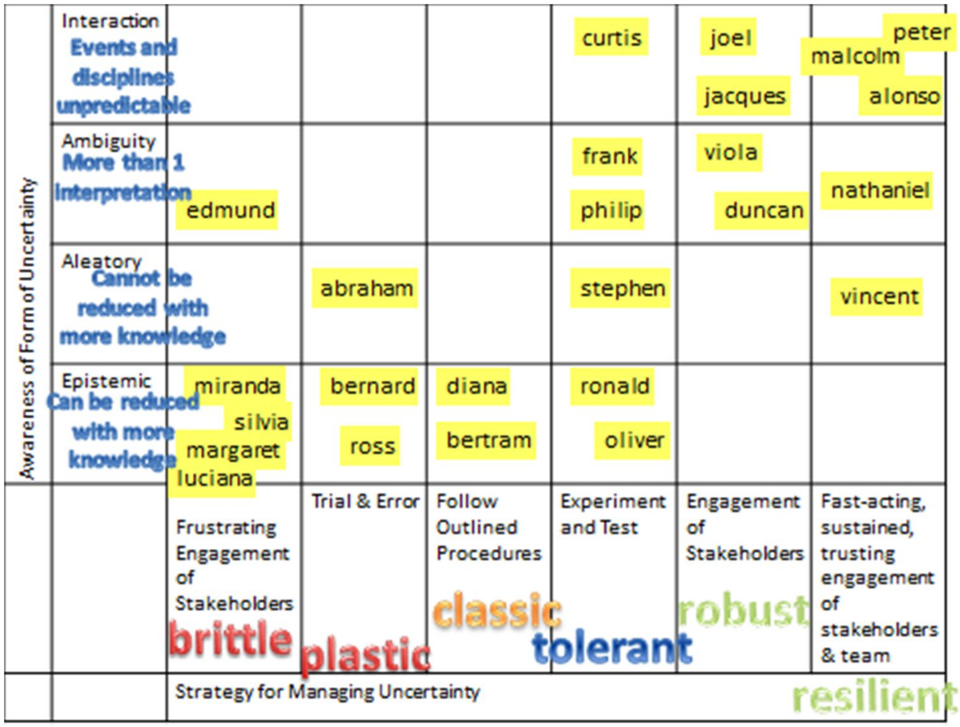

Figure C.9 Iteration 11 hierarchical outcome space.

Iteration 12 – 2015 09 28

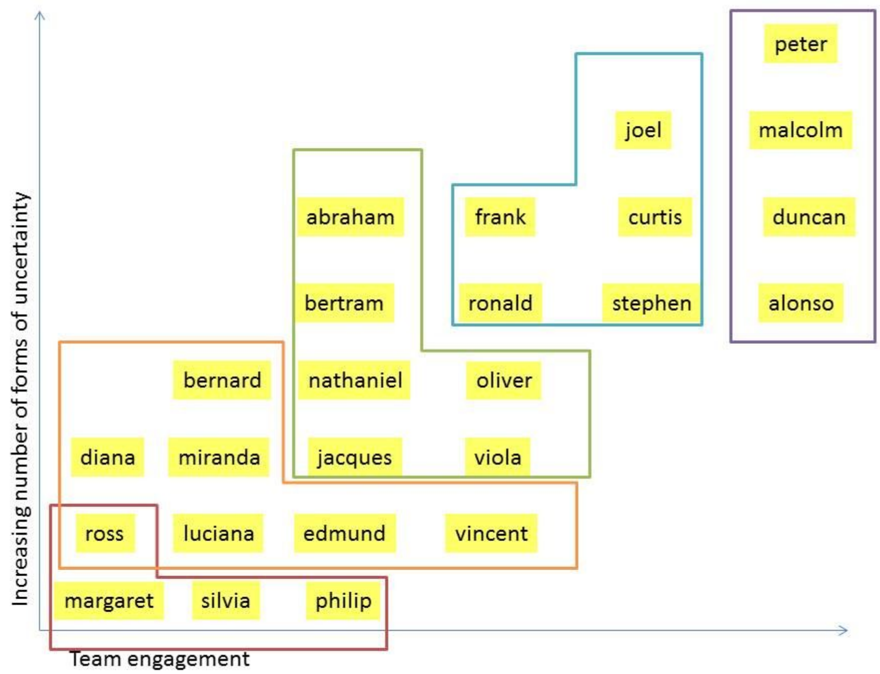

Figure C.10 Iteration 12 hierarchical outcome space.

Table C.4 Iteration 12 category description.

Category	General Description	Team Axis	Forms of Uncertainty Axis
Brittle	Uncomfortable with uncertainty or afraid of the consequences of being found ignorant by superiors; strategy or recourse is to push decisions to someone else, typically boss or team lead	Individual work, and maybe some informal peer review;	Epistemic only; they are aware that there is subject matter that they have not yet studied
Plastic	Takes solace in the fact that most things have been done before in aerospace and that there will be someone more experienced	Describes projects as team efforts, acknowledges that others have unique and complementary knowledge; peer	Epistemic uncertainty as the brittle category, but also including schedule and budget constraints;

	available to assist; will take some initiative to gather new knowledge and to justify decisions to themselves first, but also rely on superiors for decisions	review is desired	
Tolerant	Good awareness of uncertainty in the physical parts and systems is ever present and will never be eliminated, uncertainty also comes from customers and teammates in attempting to understand their goals and concerns	Describes projects as team efforts, for which they feel a significant investment or ownership in a crucial part of the project;	Epistemic uncertainty that can be reduced through planned and long term testing and experimentation; ambiguity uncertainty among teammates
Robust	Anticipating the unexpected, willing to try new methods, processes, solutions, and looking for data instead of opinion to validate and verify new solutions	Significant but possibly confrontational engagement with teammates and other stakeholders	Epistemic, ambiguity, and aleatory uncertainties; decisions hinge upon having real data and not just SME opinions
Resilient	Uncertainty is a fact of life in the business, and for the items within their control, to get the right data at the right time at the right fidelity with the right people to make decisions and even lead the market	Significant and trusting engagement with teammates and other stakeholders; have the resources, authority, and courage to deploy teammates on parallel efforts to investigate	Epistemic, ambiguity, aleatory, and interaction uncertainties; interactions could be global/political, customer-vendor, or systems within a product

Iteration 13 – 2015 10 07

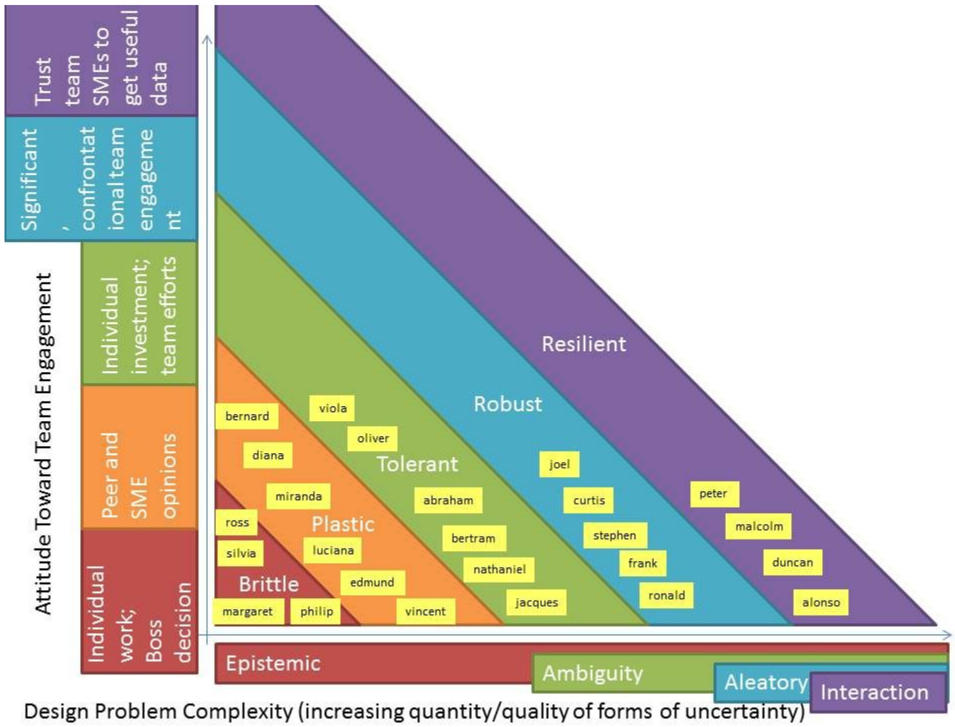

Figure C.11 Iteration 13 hierarchical outcome space.

Table C.5 Iteration 13 category description.

Category	General Description	Attitude Toward Team Axis	Problem Complexity Axis
Brittle	Uncomfortable with uncertainty or afraid of the consequences of being found ignorant by superiors; strategy or recourse is to push decisions to someone else, typically boss or team lead	Individual work, and maybe some informal peer review;	Epistemic only; they are aware that there is subject matter that they have not yet studied
Plastic	Takes solace in the fact that most things have been done before in aerospace and that	Describes projects as team efforts, acknowledges that others have unique	Epistemic uncertainty as the brittle category, but also including schedule and budget

	there will be someone more experienced available to assist; will take some initiative to gather new knowledge and to justify decisions to themselves first, but also rely on superiors for decisions	and complementary knowledge; peer review is desired, also subject matter expert opinion is solicited and not questioned	constraints;
Tolerant	Good awareness of uncertainty in the physical parts and systems is ever present and will never be eliminated, uncertainty also comes from customers and teammates in attempting to understand their goals and concerns	Describes projects as team efforts generally but not specifically, for which they feel a significant investment or ownership in a crucial part of the project;	Epistemic uncertainty that can be reduced through planned and long term testing and experimentation; ambiguity uncertainty among teammates
Robust	Anticipating the unexpected, willing to try new methods, processes, solutions, and looking for data instead of opinion to validate and verify new solutions	Significant but possibly confrontational engagement with teammates and other stakeholders	Epistemic, ambiguity, and aleatory uncertainties; decisions hinge upon having real data and not just SME opinions
Resilient	Uncertainty is a fact of life in the business, and for the items within their control, to get the right data at the right time at the right fidelity with the right people to make decisions and even lead the market	Significant and trusting engagement with teammates and other stakeholders; have the resources, authority, and courage to deploy teammates on parallel efforts to investigate	Epistemic, ambiguity, aleatory, and interaction uncertainties; interactions could be global/political, customer-vendor, or systems within a product

VITA

VITA

Antonette Theresa Cummings received her Master and Bachelor of Science in Mechanical Engineering degrees from The University of Texas at Austin. During these years of study, she worked as a research assistant for Dr. Li Shi and Dr. Joseph Koo, and was also a teaching assistant for ME130L Fluids Laboratory. She also supported various outreach activities to grow interest in STEM careers, especially for young women.

She was employed at Bell Helicopter Textron Inc in Fort Worth, Texas, for seven years after her Masters degree, specializing in math model simulation to support pilot training. In that time, she worked both on military and civilian tiltrotors. She also earned private pilot ratings in fixed wing and rotary wing aircraft.

While at Purdue University, she earned her Professional Engineer license in Texas, specializing in Thermal/Fluid Systems. She served as a teaching assistant for three and a half years in Engineering Projects in Community Service, with Dr. Oakes as her advisor. She plans to pursue a tenure-track faculty position at a teaching institution.

PUBLICATIONS

PUBLICATIONS

Bridgeman, J. O., Cummings, A. T., Narramore, J. C., & Kisor, R. (2008). *Analysis of V-22 Rotor Blade Performance Enhancements for Improved Payload.* Paper presented at the 64th AHS Forum, Montreal, Quebec, Canada.

Cardella, M. E., Buzzanell, P., Cummings, A. T., Tolbert, D., & Zoltowski, C. B. (2014). *A Tale of Two Design Contexts: Quantitative and Qualitative Explorations of Student-Instructor Interactions Amidst Ambiguity*. Paper presented at the DTRS 10: Design Thinking Research Symposium, Purdue University.

Cummings, A. T., Huff, J., Oakes, W. C., Zoltowski, C. B., & Cardella, M. E. (2014). *An Assessment Approach to Project-Based Service Learning.* Paper presented at the 120th ASEE Annual Conference and Exposition.

Cummings, A. T., & Oakes, W. C. (2015). *Helicopter Aerodynamics and Design Course Developed from a Research Informed Framework.* Paper presented at the 122nd ASEE Annual Conference & Exposition, Seattle, WA.

Cummings, A. T., Shafaat, A., & Oakes, W. C. (2015). *Using Robust Design as a Conceptual Framework to Understand Expertise*. Paper presented at the Frontiers in Education, El Paso, Texas.

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