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Mapping Design Processes to Practicing Engineers' Perceptions of Uncertainty in Aerospace Design

Marty Mathews Jr., University of Wisconsin, Platteville

I am pursuing my BSME from UW-Platteville, with an expected graduation in May of 2018.

Dr. Antonette T. Cummings P.E., University of Wisconsin, Platteville

Antonette T. Cummings is an Assistant Professor in Mechanical Engineering at the University of Wisconsin - Platteville. She earned her Ph.D. in Engineering Education at Purdue University. She earned her BSME and MSME at the University of Texas at Austin. She worked in aerodynamics and math modeling at Bell Helicopter for seven years, earning airplane and helicopter private pilot ratings. She has a Professional Engineer license in Texas in Thermal/Fluid Systems.

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Student Paper

Abstract

Uncertainty is an unavoidable aspect of design. We discovered there are many different types of uncertainty in complex systems, however these can be condensed into a few categories. Significant research exists on epistemic uncertainty, but proper understanding and management of other forms of uncertainty are less thoroughly explored. We investigated previous research in the context of design to assist in better defining and understanding uncertainty. We conducted this research with the intent of designing learning interventions to improve engineering students' ability to understand and manage uncertainty in design. From previous research we learned one of the most significant factors in successfully managing uncertainty is incorporating teamwork. While there is significant research on the topic of design, and to a lesser extent uncertainty, there is virtually no existing research pertaining to the intersection of uncertainty, design, and teamwork. We used the qualitative research methodology of constructivism, and included sampling of a population of engineers that has a broader view of various forms of uncertainty in aerospace design. We combined this methodology with exploration of existing research on the topics of uncertainty, design, and teamwork, and compared to published works on various design methods. We found an existing design methodology outside of the common engineering methodologies that aligns with the experiences of our study participants. We recommend further research to test the impact to students' learning to manage uncertainty in design when employing this particular design methodology.

Introduction

The purpose of this research is to develop learning interventions to increase student understanding of uncertainty in aerospace design. We are building on previous research that developed a hierarchy of increasing comprehensiveness of understanding of uncertainty in design decisions [1]. The previous research involved interviewing twenty five engineers in the aerospace industry. A surprising result from this research is that aerospace engineers must simultaneously increase their understanding of teamwork in order to be successful at managing multiple categories of uncertainty in aerospace design [2]. Now that we know more about what largely comprehensive understanding includes, the next step is to investigate strategies for students to improve their own understanding of multiple forms of uncertainty in aerospace design of complex systems.

The goal of our current research in this paper is to identify common themes in the design experiences of the engineers at the highest understanding of uncertainty and to compare our results with existing design methodologies. Our ultimate intent is to determine a structure that can be utilized as a classroom method to increase student understanding and managing uncertainty in a design process. Perhaps from these themes we can determine how effectively managing uncertainty in design can be taught to aerospace students or engineering students in general.

We believe our results are broadly applicable to most engineering disciplines, even though we are starting with a sample of aerospace engineers. Risk is a huge factor in aerospace, and is an uncertain element that must be understood and managed properly in order to successfully design. Aerospace engineers in particular know to address risk early and thoroughly [3]. Generally speaking, employers are increasingly seeking engineers who are flexible and adaptable [4] as the problems they are solving are increasingly complex [5] and uncertain.

Literature Review & Research Question

The word uncertainty has varying definitions and classifications across disciplines, so it needs to be defined here in the case of complex aerospace systems as the context of our research participants' design experiences. Thunnissen classified four types of uncertainty [2]. The first type, *ambiguity*, is defined as imprecise terms and expressions in general communication. Second, *epistemic* uncertainty is a "lack of knowledge or information in any phase or activity of the modeling process… which can be further classified into *model*, *phenomenological,* and *behavioral* uncertainty". Epistemic uncertainty can often be reduced by obtaining more knowledge. Third, *aleatory* uncertainty is "inherent variation associated with a physical system or environment under consideration", often represented with probability distributions. Fourth, and perhaps significant in complex multidisciplinary systems, *interaction* uncertainty "arises from unanticipated interaction of many events and/or disciplines, each of which might, in principle, be or should have been foreseeable". Typical undergraduate engineering courses may focus on epistemic and aleatory uncertainties, and there may still be unquantifiable sources of ambiguity and interaction uncertainty.

To assist in designing a learning intervention we explored existing research regarding uncertainty in design and included recent research regarding teamwork as a significant component. We triangulate the unexplored research space using the keyword search terms of "uncertainty", "design", and "teamwork". We took a systematic approach to exploring published literature, including publications from the professional engineering societies. Our primary source was the American Society of Mechanical Engineering, due to access using University resources. A plethora of research volume exists regarding the combination of "uncertainty" and "design" with over 10,000 articles existing in the ASME digital collection alone. There is also significant research regarding "teamwork", with over 100 articles found. However when exploring the union of uncertainty, design, and teamwork, there is very little existing research that explores these three unique aspects, with only 6 articles [6-11] found including these three keywords.

With so much research in design, and so little research on uncertainty, design, and teamwork combined, we ask the research question: which existing design methodologies align closely with experienced aerospace engineers' perception of uncertainty, teamwork, and design?

The purpose of this study is to correlate existing theories about design and teamwork with recent results about an engineer's increased ability to manage uncertainty. Our overarching goal is to improve the quality of an engineering student's education in managing uncertainty in design decisions. Our proposition is that while engineering education has advocated design methodologies that indirectly address uncertainty and teamwork, such as the human-centered design approach [12, 13] and project-based service learning [14, 15], we may find a more direct approach to design, uncertainty, and teamwork outside of the engineering discipline.

Research Methodology and Description of Data

We employ constructivism as the theoretical framework to explore our research question. Typically in constructivism, we consider the foundational questions "How have the people in this setting constructed reality? What are their reported perception, 'truths', explanations, beliefs, and world-view? What are the consequences of their constructions for their behaviors and for those with whom they interact?" [16]. In our study, our participants have developed their own understanding of uncertainty through their uniquely situated experiences in aerospace engineering design, and this influences how they approach design projects and design decisions. Specifically, previous research indicates an engineer's broader understanding of uncertainty in design correlates with engaging more skillfully with others as team members being the primary management strategy [1]. This qualitative framework guided the design of the study, data collection methods, and analysis methods.

Our in-depth analysis focuses on the transcripts of interviews exploring the experiences of a subset of engineers from previous recent research [1], shown in Table 1, whose perspectives are the most comprehensive understanding of uncertainty in design. They have been empowered to make decisions in their respective companies, and are all employed in the aerospace industry, either in the US or abroad. The data on their experiences were previously collected using qualitative naturalistic inquiry through semi-structured interviews. The participants were asked about their experience of decision-making in design, their experience of uncertainty in design, and any reflections they had on learning about uncertainty. All of the participants in the study did so of their own volition, and their interview transcripts were de-identified to protect them and their employers. The unit of analysis for this study is each critical design experience described by these engineers.

Table 1. Demographics of participants in this study.

Pseudonym	Years of Experience	Gender	Type of Employer	Job Title	Degree	Pilot
Peter	32	Male	Subsystems	Chief Technical Officer	BS Electrical Eng’g	no
Malcolm	28	Male	Subsystems	Senior Program Manager	MS International Management	no
Duncan	22	Male	Airframe & Powerplant Integrator	Chief Engineer	MS Aero Eng’g	no
Alonso	16	Male	Airframe & Powerplant Integrator	Integration Leader	MS Systems Eng’g	no
Joel	26	Male	Airframe & Powerplant Integrator	Director	BS Aero Eng’g	yes
Frank	18	Male	Materials	Process Engineer	MS Industrial Technology	no
Curtis	16	Male	Operational & Environment Scenario	Technical Fellow	MS Aviation Science	yes
Stephen	11	Male	Airframe & Powerplant Integrator	Engineer V	MS Mech Eng’g	yes
Ronald	6	Male	Airframe & Powerplant Integrator	Project engineer	BS Aero Eng’g	yes

Results of Transcript Analysis

Data compiled from the nine engineers with the most comprehensive understanding of managing uncertainty in design yielded interesting results. Several important themes common to these aerospace engineers were identified from the interview transcripts. We present a representative quote and several similar, though truncated, quotes from other participants to illustrate the themes. Each of these themes is an aspect of how the participants have constructed their understanding of and managing uncertainty in design.

Theme 1: Managing uncertainty can be learned, but none learned to do so in school

A common conclusion from the participants is that the ability to manage uncertainty in design can be learned. This was most succinctly stated by Stephen who responded to a question about whether he approaches projects the same way at the beginning of his career versus where he was now by simply stating “No. Again it’s a learned experience.” The participants explained that there were five main factors that they felt enhanced their learning: repetition, occurrence of failure, access to mentors, a need to pursue more knowledge, and using a design process.

First, learning to manage uncertainty includes repeated experience working on design projects. In response to a question regarding any formal training in uncertainty, Alonso responded:

> *There is some training when I did systems engineering classes but my formal training I think it's, my training is really with my job… the project I'm in, is fairly complex so I can say that it has been a good training.*

Frank articulated the same idea, stating "I've learned a lot just through repetitions of the process." Joel explained this idea of repeated experience by saying "I think you just need to know, whatever that learning objective is, just to see it over and over again."

Second, learning experiences included failure. In sharing how to represent different aspects of the design, Frank stated "…if you don't present failures, then we're not learning anything." Stephen echoed a similar sentiment, adding "…you're going to make mistakes. Just don't let it get you down. Just try to learn from your mistakes." Curtis added that "…just because you failed doesn't mean that you're a failure," and elaborated by saying "The idea is to fail early when it's cheap."

Third, having a mentor or interacting with people possessing knowledge regarding the design is another theme of learning how to manage uncertainty. Peter said simply "…I had a great mentor…that helped shape me in my thinking as a leader." Duncan shared that through these sorts of interactions "…they may tell you a few tricks on how you go about doing certain things and then you do that." Alonso gave a personal perspective, sharing "…people interacting on how they organize the work and how they solve the problem that was… I got to learn, that was my learning experience in this field." Ronald gave another perspective regarding uncertainty and learning through mentoring or interaction with someone possessing more knowledge. He shared that when dealing with design issues:

> *They might be uncertainties to you, but probably somebody senior has dealt with the problem or something similar enough that he can give advice on how to answer these questions… Those mentor type relationships are by far the most helpful… The odds are that someone else has dealt with that probably more and has a solution.*

A fourth key factor in learning was being active in pursuing knowledge. Reading, research, technical experiences, and being engaged were all factors mentioned by our interviewees that expanded their knowledge and were identified as learning experiences that improved their ability to manage uncertainty. Alonso explained:

> *[I] had the opportunity to attend to every meeting or part of the work that was done. In that case as well I was learning really like a student doing very small tasks and participating… That was probably one of the best training that I had in the approach to uncertainty and let's say design*

Curtis explained this active pursuit of knowledge by saying “The managing uncertainty that I’ve had, well, some of its self-taught, so I read…” Duncan confirmed this idea, stating it “…probably comes between literature, internal studying that maybe going on with the company about different things…something like that you’ve read.”

Fifth, the participants believe that there is a process used to assist in managing uncertainty in design. While a specific process was not identified, the extensive use of processes as a means of managing uncertainty was clear. Duncan stated simply that with “any sort of engineering design… There is a process”. Frank explained “It’s more of a broad, then work down into a narrow decision-making process… a thought-map process.” Another explanation of a process used by Curtis was “Start in the known. Say this is unknown. Okay, well 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.” Alonso declared “The process is to reduce the variables, that’s all what you have to do.” Joel described a “failure management strategy” as a process involved in design. This consensus indicates the importance of identifying a process aerospace students can use to assist in the design process.

The second part of this theme is that these engineers believed that many of these things are not learned in school. It was stated that there is no hands on experience in school, little to no experience in design, or exposure to uncertainty or decision making. Ronald responded to a question regarding formal training in managing uncertainty with “I would say that all the dealing with uncertainty education I had was on the job, experience in learning how to fly.” Peter shared that “I actually worked in the factory also which I think really helped shape me as a leader.” When asked whether he felt like he had formal training in managing uncertainty in design, Duncan said “I wouldn’t say from my college experience... I would say from the company standpoint within those academics, probably not.” Ronald shared his opinion:

> *I think schools could do a much better job of exposing students to more, broader non-academic topics.… based on my experience and talking with other undergraduate engineers, that very few of them know how to do things in a real world sort of way.*

Peter identified a more specific issue: “When you went to school there wasn’t a class on effective decision making …nobody really taught you how to make effective decisions.” Frank echoed this sentiment, replying to a question asking if he could think of an experience that prepared him to handle things he didn’t know by saying “You know, going back to my college days, I can’t think of a class that really did prepare me for what you just mentioned.” Ronald stated simply “I got my bachelor’s degree, and I immediately felt like I wasn’t really qualified to do anything for real.” All of these point to the need for an improved method of assisting aerospace students at the undergraduate level in improving in the area of understanding and effectively managing uncertainty in the design environment.

Theme 2: Define the design and constraints

A critical component identified is to define the design or problem being presented. In order to produce an effective design, the issue must be properly understood. As shared by Alonso, "you have to manage and reduce the variable once at a time." An explanation given by Steven was "there are better ways to do things almost always when you're working a solution, but hey, maybe your company can't afford the $200,000 software to help you do it." Performance requirements, budget limitations, time constraints, and safety concerns must all be accounted for and satisfactorily managed for a design to be a success. Ronald explained "It was more to decide whether we could reasonably manufacture these consistently, so that we could be comfortable with the requirements that we were dealing with." Understanding the parameters is vital to ensuring the success of failure of a design.

A crucial part of defining the designing is considering stakeholders. It is important with any design, according to Peter, is to be "Making sure that it encompasses everybody's stakeholders requirements around it whether it's in the manufacturing side, whether it's in the quality side, whether it's in the customer side… Do we really understand what the buying decisions are of our customers?"

A finer aspect of considering the stakeholder is to consider the human interaction with a design. Curtis stated that in all design decisions described "an operator was involved." As explained by Duncan, "there's varying customers that you're answering to both internally in terms of your management, and external, then usually for a defense contractor, a government entity of some sort." If the product will be built and used by human beings, then designing it to interface well with a human being is important to effective design work. This idea also includes considering the customer or desired consumer, and designing with their preferences and requirements in mind.

Theme 3: Teamwork

Teamwork was revealed to be the critical component to successfully managing a design. Malcolm explained this more broadly by saying "We have to have a structure in place to make sure that ultimately we fully meet these requirements that we signed up to deliver." Describing an important design decision that needed to be made, Malcolm said "We ended up working closely with my [company3] team… we sat down with my team… We developed a plan of recovery".

Ronald explained a noteworthy design experience where he worked with "…a relatively small group… with a few design engineers familiar with that area." Ronald also said that in his experience with his company he was part of "an integrated team," with individuals having various responsibilities within the team, "you'd have one person that was responsible for aerodynamics, another who was responsible for stress analysis, one person responsible for mechanical systems, one project engineer who was overseeing the team."

This detailed description helps provide more insight into what an effective team structure might look like. When discussing his range of responsibilities, Alonso mentioned "the design part is not in my team" when explaining a specific design scenario. This mention of his team implies a constant involvement with a specific group of individuals. When responding later in the interview to a question about who would have been involved in a particular design he had described, Alonso said "The people that are involved are of course my team of course." Again, his response clearly indicates the fundamental nature of teamwork to his design methodology. He went on to state candidly "if you don't have with you I mean good people you don't go anywhere." When responding to the same question regarding whether other people were involved in a design process he was describing, Frank shared "We had a team of probably about six or seven people." While being open to outside assistance, personal responsibility and ownership of a project is important, as Malcolm explained, "you have to find the decision maker who has the stand of authority to truly make and own that task." These findings clearly demonstrate the assumed presence and declared effectiveness of teamwork from these engineers.

In relation to this idea of teamwork, our research revealed communication is a crucial part of design, and includes cultivating relationships with other experts in and outside of the company an individual works for. When describing resources and tools to help with managing uncertainty in design, Frank said "It's a matter of making relationships and communicating with others in trying to avoid reinventing the wheel …communication and building relationships with the people you need to deal with to get things done." Steven explained this importance by sharing that to solve a problem sometimes "you've got to talk with a lot of people… let them know that they know more about their topic than you'd know about their topic." Alonso agreed with this point about communication, stating that at times in order to make a design decision people "need to continuously to exchange their information." Peter was pointed with relationships, stating

> *It's a competitive landscape and it becomes a lot around relationships… Our sales people and our engineers are really working very hard to be very integral to their key relationships with inside those customers.*

Part of this communication and relating involves being open to ideas. Co-workers, peers, and new ideas can often be helpful in solving a design problem, and should be considered. As explained by Alonso, "basically you have to stay always open and being able to change your approach." In addition to being open to ideas from within, seeking outside help can also be useful. Ronald explained that "you reach out to other organizations or companies that may have done testing in a similar way." Alternatively, Joel explained how problems can result when this doesn't happen. He shared a story of working with individuals who, when working with a colleague "were very resistant into incorporating his opinion or his results into the effort, and I would say long term what it allowed, what it made them do is hire a thermo-dynamicist on their team so they can take a look at it." As reiterated by Alonso, it is crucial not to "leave something outside just because you don't have a good relation with the person." This resistance to the ideas of others can be detrimental to a design process. Getting buy-in from all team members is central to an effective design.

Theme 4: Understand and manage the uncertainty

To navigate a design it is important to understand and manage the uncertain aspects of the design. Risk, ambiguity, variables, confidence, margin, and lack of knowledge are alternative vocabulary terms for uncertainty identified by the participants. Uncertainty is always present in a design project, and Curtis declared:

> *Even if you think there are no unknowns, there are unknowns… Let's approach it so that the risk is less, so that we won't go straight to the endpoint, or not do this step. Measure it and manage it and budget for it.*

Joel added another dimension to this idea, sharing "there are a lot of ways that you can go ahead and reduce the risk so that it is manageable." Defining this uncertainty helps the student to understand what uncertainty is present.

Once uncertainty is identified there are several ways of navigating that uncertainty. Reading, research, developing pattern recognition from multiple scenarios and past experiences, developing useful skills, running multiple iterations, and history within an area of emphasis all assist in managing uncertainty. In addressing how to go about solving a problem, Duncan listed "Reading things backing up your assumptions…" as an important method. Duncan explained that in figuring out design details he didn't know "What I did have was access to battle damage reports, where I could read about each engagement that resulted in a hit on an aircraft and I could get a general idea. So I did some research…" Stephen provided more detail regarding useful subject material for reading in response to a question regarding how to determine possible solutions. He stated "You start with the back of the envelope so I went to the textbooks, determined some figures of merit that you might look at if you're looking at tail design."

Whether it is personal or belonging to someone else, history or experience within an area of emphases can also be useful. Joel stated a key component was "times at bat…to recognize these times and how many time show many can you see it, can we do it through scenario?" Frank shared a design decision he was involved with "that was based off of my prior experience in working with this material and similar materials like that." History can also be an ally, and according to Ronald, "presumably, someone 10 or 50 years ago has done that testing for you."

While this history can be useful, developing skills is an important piece to solving a design issue. Duncan expanded on this idea, stating "just talking about CAD gets you to a point where you have certain basic skills that could apply to any particular program and those are skills that are useful to you from an engineering standpoint to solving a problem." In using these skills multiple iterations are often required to obtain the best solution. Duncan explained "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."

Theme 5: Make decisions

When designing anything, decisions must be made. Many times these decisions relate to the uncertainty of the design. Risk is part of design, and decisions need to be made on waiting for more information or accepting the risk. Joel said regarding decisions:

> *[The] other thing about uncertainty is you can't stop, not making a decision or make the decision in itself, so you can't stop… You just live with uncertainty. It just kind of trains you for that, 'A decision's got to be made here in five minutes. Come on. Let's keep moving'.*

Tradeoffs must be considered, and balanced within the uncertainty and design parameters identified earlier. To exemplify this idea Malcolm stated "Whenever you make those choices, there's always decisions or collateral things that have to happen with it." Curtis said:

> *Very, very rarely if ever is there a design decision that's made that doesn't have a downside somewhere… Know that every design decision has a positive and negative trade, and the unknowns and the risk, and like you said, managing the unknowns.*

Joel confirmed this idea, saying "I think, every engineering design, every procedure is a compromise, so you could figure on something that was enough of a compromise that everybody can agree and sign off on a clearance." Stephen added another perspective, saying "There are better ways to do things almost always when you're working a solution, but hey, maybe your company can't afford the $200,000 software to help you do it." This sheds light on the tradeoffs that are constantly necessary when pursuing a design solution.

Theme 6: Test and experiment often

Finally a vital part of a successful design is testing and experimenting often. Ronald stated "the uncertainty itself makes you more likely to checking more things, makes you test more and inspect more." Malcolm explained that he had reached a point in a design project "where we need flight test to verify requirements." Once the design has been defined and decisions have been made, it is imperative to experiment to help eliminate uncertainty within the design, and once the design is nearing completion to test repeatedly to ensure proper and effective design completion. As shared by Joel, "There's more and more testing and you get a little smarter with each day…" Curtis provided a broader explanation, explaining the necessity:

> *Prototyping early, rigorous testing throughout, so that you fail, break the thing… If you're designing and you're building new stuff, you're going to fail. The idea is to fail early when it's cheap. And that goes to goes back to the test and the prototyping.*

Results of Design Process Investigation

We consider now which existing design and instruction methodologies closely align with themes 2 through 6 identified in our transcript analysis. The word *design* is used across multiple disciplines [17] and we do not want to limit our search to engineering sources only. Rather, our participants, most with engineering degrees, indicated in the first theme above that their academic learning experience did not specifically address managing different forms of uncertainty. This perception suggests that we should consider whether there are design methodologies even in non-engineering disciplines that more directly integrate teamwork and uncertainty. We start our search within engineering teaching, learning, and design contexts first.

Engineering design textbooks are widely available for undergraduates, including Raymer's *Aircraft Design* [18] for aerospace applications and more in the closely related mechanical engineering field. Because aircraft product design is complex by itself, the textbook authors tend to mention obliquely that there are other continuously changing factors that will affect how and why we design. These textbooks often focus on modeling, prototypes, and experimentation, which can introduce epistemic uncertainty, but very rarely do these textbooks have space to introduce other forms of uncertainty or teamwork.

In project-based service learning (PBSL) [14], defining the design and scope of the project is the Phase 1 step and setting requirements are in Phase 2. Risk assessment comes fairly late in the detailed design Phase 4, but early experimentation and the possibility of failure are introduced in Phase 2 with mock-ups and simple prototypes. Each phase concludes with a decision-making gate and a description of the necessary attributes to proceed with more design effort. In this design process, instructors include team-building activities at the beginning of the semester and follow an iterative design process that centers around stakeholders at every phase of the design process. Teamwork and uncertainty are implied, but not formalized attributes of the design process.

In Human-Centered Design [15], we find that teamwork is highly encouraged, which should impact the innovation of the final design. For example, IDEO provides a human-centered design toolkit [12] and summarizes the phases of the design process as "Hear, Create, Deliver". It then advocates multidisciplinary teams as a best practice, which may mean 3 to 8 teammates, keeping a gender balance, and disciplinary and educational backgrounds. This methodology also includes engaging stakeholders as co-designers in almost every phase of the design process, which makes this design process unique among many choices of design process. However, the aspect of uncertainty is implied or assumed, but not distinct in the design process.

We expanded our search of formalized design processes by using a Compendium of Models by Dubberly [19]. The graphics range from linear block diagrams to complicated feedback loops with more than twelve steps. The applications include software design, in which human-centered design has roots, and mechanical design, which would presumably lead to aerospace design. As with the other design processes we investigated, the word "team" is present outside of the design process blocks, except for one.

The American Institute of Graphic Arts (AIGA) presented a twelve step process where teamwork is expressly step eight, shown in Table 2. The theme of learning from failure is step twelve. Delineating the tough choices in step seven aligns with our participants' theme of making decisions, knowing that risk is present. The themes of defining the end state and the process to achieve the end state are steps two and three of this process. Theme 4 managing uncertainty through research and past experience aligns with step five of this process. Overall, this process highlights each of the themes we discovered from our participants' transcripts.

Table 2. Reproduction of Mok and Yamashita's 2003 Process of Designing Solutions, from Dubberly [19].

Defining the problem			
1 Defining the problem	2 Envisioning the desired end state (knowing what victory looks like)	3 Defining the approach by which victory can be achieved	4 Inciting support and then action
Innovating			
5 Seeking insight to inform the prototyping of the solution	6 Prototyping potential solutions	7 Delineating the tough choices	8 Enabling the team to work as a team
Generating value			
9 Choosing the best solution then activating it	10 Making sure people know about your solution	11 Selling the solution	12 Rapidly learning and "tacking" based on your successes and failures

Limitations and Boundaries to this Study

The applicability of the results and recommendations of this small study are bounded by several factors. First, the data collection methodology for the interviews included self-selection by the participants; no women with similar years of experience accepted the invitations to be interviewed. Second, for time savings, we constrained the literature search for design methodologies essentially to a single source, a compendium of models, instead of an exhaustive search of published literature. Third, the experiences and biases of the researchers influence the analysis of the data. The first author, as an undergraduate researcher, has not yet completed a senior engineering design experience, which positions him like an outsider looking in, or as a novice observing experts. The second author has teaching experience in project-based service learning using human-centered design and so proposed these approaches as a baseline for comparing design methodologies. We acknowledge that these limiting factors lead us to the next step for a pilot study to explore further our proposition.

Conclusions and Recommendations

Managing multiple forms of uncertainty and making engineering decisions is a learnable skill. For our participants, this broadly comprehensive ability to design often has not come from undergraduate education, but they agree that it can be learned. Our participants constructed their understanding of uncertainty through memorable experiences, and those experiences had significant commonality. Their learning experience contained crucial attributes: 1) The design must be properly defined and parameters understood; 2) Teamwork is integral to success in managing uncertainty in design; 3) Understanding and managing uncertainty is vital to exemplary design; 4) Making decisions important component of design; and 5) Abundant testing and experimenting is important to design. We proposed that there must be an existing design process that can be used for classroom instruction for this learnable skill.

Mok and Yamashita, of the American Institute of Graphic Arts, outlined a twelve-step process to explain how they design. This design process closely matches and the themes described by the participants in this research. This design process may provide an effective template for aerospace engineering design of complex systems, including teamwork and uncertainty. We recommend that this design process be piloted in a classroom setting as a means of instructing students on how to better manage uncertainty in design.

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