UNDERSTANDING THE DEVELOPMENT AND IMPLEMENTATION OF HEURISTICS AND BIASES IN DESIGN

A Dissertation Presented to The Academic Faculty

by

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SUMMARY

Heuristics are rules of thumb used by designers to save time and resources in exchange for satisfactory, but not necessarily optimal, solutions. However, there is a large knowledge gap in understanding how heuristics are developed, retrieved, employed, and modified by designers. Having a better awareness of one's own set of heuristics can be beneficial for relaying to other team members, improving a team's training processes, and aiding others on their path to design expertise. Similarly, awareness of heuristics used by other team members could aid a designer's understanding of decisions outside of their own expertise and the collective vision for the team's final design. Ultimately, describing how heuristics are used may lead to a more normative approach to heuristics, through determining how one heuristic may add more value to the design process over another. This justification should lead to more effective decision making in design. To do this, the heuristics and their characteristics must be extracted using a repeatable scientific research methodology. To that end, the following research questions are addressed within this dissertation:

- How should the methodology for extracting heuristics be improved such that we may assess the value a heuristic brings to the design process?
- 2) What aspects of heuristics and design environments should be considered during documentation of heuristics in a repository?
- 3) How might heuristics be characterized and classified to understand their impact on design processes?

This dissertation presents four exploratory case studies aimed at identifying improvements to heuristic extraction methodology, with participants ranging from space mission concept design, advanced manufacturing, and graduate student design teams. A framework for documenting and updating heuristic knowledge over time is formed based on statistically significant correlations of heuristic attributes, specifically in regards to how often a heuristic is used, how the reliable the heuristic is perceived, and how often the heuristic evolves. Lastly, an alternate perspective of heuristics as an error management bias is highlighted and discussed.

CHAPTER 1. INTRODUCTION

1.1 Motivation

Heuristics are rules of thumb providing guidance for choosing design actions, given the current state of the design process. A common example of a design process heuristic is: "When exploring for new ideas, alternate between convergent and divergent thinking." They are used by designers to save time and resources in exchange for satisfactory, but not necessarily optimal, solutions. These rules of thumb are known to be developed through a designer's experiences (among other sources), but there is a large knowledge gap in understanding how heuristics are retrieved and employed by designers. Additionally, designers may not even be aware of some heuristics they engage during design. Having a better awareness of one's own set of heuristics could improve the design process in many ways. Heuristics from experience can be relayed to new team members, improve training processes, and shorten the learning curve on the road to design expertise. Understanding the heuristics used by team members outside of a designer's own domain or expertise may potentially improve the team's shared mental model of the design. Lastly, describing how heuristics are used may lead to prescribing how heuristics should be used. Being able to justify the use of one heuristic over another will lead to more effective decision making in design. To do this, the heuristics must first be obtained using a repeatable scientific research methodology. Then, we must determine and obtain measurable critical attributes that a designer can use to determine which heuristic(s) is(are) most valuable, given the

design applicability context. To that end, the following research questions are addressed within this dissertation research:

- 1) How should the methodology for extracting heuristics be improved such that we may assess the value a heuristic brings to the design process?
- 2) What aspects of heuristics and design environments should be considered during documentation of heuristics in a repository?
- 3) How might heuristics be characterized and classified to understand their impact on design processes?

The main goal of this research is to provide designers with guidance for choosing the heuristics adding the most value to their design in any given context. This dissertation is comprised of four studies. All four studies provide insight into characteristics of heuristics in design and the methods for extracting them. Study I explored direct corroboration with designers for extraction and characterization of their own heuristics. The aim was to correlate heuristic attributes in a manner that visualizes the value they bring to the design context. Study II extracted additional process heuristics from the same design team, in hopes of analyzing how designers perceived their own processes. This study also obtained feedback through a focus group regarding which implementation factors should be considered when building a repository of heuristics for a design team. Study III focused on heuristics from a cognitive bias perspective, observing how heuristics may also be implemented as an error management bias. This is assessed through design teams within a graduate level engineering design course. Lastly, Study IV observed how heuristics evolve

within expert designers in advanced manufacturing, and how this impacts the value of those heuristics over time. The results of this study provide design teams and individuals with a framework for documenting and updating heuristic knowledge as it evolves over time, along with characteristics that may be used to assess the heuristics' value to the design process.

Von der Weth and Frankenberger stress the need for heuristic competence in design because it gives designers confidence to attack novel problems [1]. They define heuristic competence as having possession of a pool of heuristic knowledge and the ability to appropriately apply that knowledge for problem solving. On the other side, less heuristically competent people may avoid new situations because of previous failures with heuristics. Maier similarly believes "knowing when and how to use a heuristic is as important as knowing what and why [2]." By understanding various aspects of how heuristics are developed and implemented, this dissertation ultimately contributes to advancing heuristic competence within designers.

1.2 Overview

In the following Background chapter, an overview of heuristics and biases will be provided, as well as previous methods used to study them. Then, four additional chapters discuss four separate studies in detail. Chapter three presents a series of interviews of surveys with members of a single team at NASA's Jet Propulsion Lab. This study extracts heuristics through interviews and characterizes those heuristics through the surveys. Correlations are made with the survey data. Chapter four presents a second study with this design team where a focus group obtains the team's thoughts on building a heuristic repository, followed by another heuristic extraction process. Those heuristics are discussed based on how they were written by the participants. Chapter five presents a study of cognitive bias in graduate student design teams, in hopes of understanding where some major biases may fall in their process and how those biases may be viewed from an error management perspective. Chapter six ends the set of studies by presenting a series of design journals, interviews, and surveys with users of advanced manufacturing technology. Similar to Chapter three, this study delivers a set of extracted heuristics when are then characterized through surveys, with statistically significant correlations produced by comparing survey responses. Chapters seven through ten present the conclusions, limitations, contributions, and future work, respectively.

CHAPTER 2. BACKGROUND

2.1 History of Decision Making and Heuristics

In psychology and economics, heuristics are known as "procedures for problem solving that function by reducing the number of possible alternatives and solutions and thereby increasing the chances of a solution" [3]. They are a means for simplifying information processing. In engineering, Koen defines heuristics as strategies that are potentially fallible but give direction towards solving a problem [4]. They are used by the designer to guide, discover, and reveal. They do not guarantee solutions, may contradict other heuristics, reduce search time, and depend on the context rather than an absolute standard. Using these characteristics, Koen argues that "all engineering is heuristic." Fu et al. analyzed many different definitions of heuristics and presented a composite definition of heuristics in design as " a context-dependent directive, based on intuition, tacit knowledge, or experiential understanding, which provides design process direction to increase the chance of reaching a satisfactory but not necessarily optimal solution" [5].

Historically, heuristics have often been viewed in contrast to other prescriptive decision making methods. The "rational" decision making model began with von Neumann and Morgenstern using a set of axioms to assign outcomes of an event with a value known as *utility* [6]. Utility theory considers the uncertainty of the event, as well as the decision maker's risk preferences. From the perspective of utility theory, a rational decision maker should make decisions connected to the highest expected utility. Howard assisted in the development of *decision analysis* by combining utility theory with Bayesian statistics, a

way to update probabilities given new information [7]. For some time, it was assumed that humans naturally make decisions in a manner consistent with these models. For example, Friedman and Savage hypothesized that it is realistic to assume people have consistent preferences that could be described by a utility, with the objective to make this utility as large as possible. They use an expert billiards player as an example: while the player may not know or perform all the mathematical equations behind each potential shot, they will consistently choose the shot they believe will most likely result in the preferred outcome [8].

Tversky and Kahneman led the way in presenting how humans rely on heuristics that can bias decision making such that the decisions are not consistent with utility theory [9]. One well noted example is the "representativeness" heuristic, in which people will evaluate probabilities based on similarities. The probability that A belongs to B is evaluated by the degree to which A resembles B. This process may result in severe errors in judgement when factors such as prior probability or sample size are not considered. As an example, Tversky and Kahneman describe a hypothetical individual, Steve, as shy, tidy, meek, and having a passion for order. They then ask subjects to judge which profession Steve is likely to hold, among farmer, salesman, airline pilot, librarian or physician. They find that "the probability that Steve is a librarian, for example, is assessed by the degree to which his is representative of, or similar to, the stereotype of a librarian," rather than the relative proportion of the population that comprises librarians [9]. Tversky and Kahneman did not intend for heuristics to prove humans behave irrationally, but rather to show that the existing models of rationality did not accurately describe humans [7, 10]. Other researchers attempt to justify heuristics as a rational form of decision making, particularly when viewed from an evolutionary standpoint. Haselton et al. suggest natural selection has allowed humans to deploy heuristics in a way that best serves the "fitness" of humans over time [11]. Lo also views heuristics as developed for survival in a particular environment [12]. For example, heuristics developed by investors during the Great Depression would differ from those in a booming economy. It would not be fair to consider either sets of heuristics irrational, because they were shaped to survive a specific economic environment. As this environment changes, the heuristics may no longer be beneficial, and new heuristics must be acquired.

Gigerenzer believes heuristics can exist as a rational decision making tool alongside logic and probability theory, where each tool is valid given the right environment [13]. The heuristics have "ecological rationality" in situations where they are not just cognitive limitations, but allow for better decision making in situations in which other methods may struggle. For example, the "1/N" heuristic (allocating money equally to *N* number of assets in an investment portfolio) has been shown to perform better than the portfolio optimization proposed by Markowitz, when the environment contains large uncertainty, many assets, and smaller learning samples [14].

The history of decision making is relevant to this dissertation for its ability to place relative value on each decision alternative in question. This framework can potentially be extended to heuristics for justifying when one heuristic should be used over another, if the heuristics are documented and described in a sufficient manner. Gigerenzer believed the results from Tversky and Kahneman were limited because they failed to address the environment in which heuristics (such as the *representativeness* heuristic) performed adequately or poorly [15]. This was not to discredit their work, but rather to emphasize the importance of context when considering heuristics in place of other decision making tools. Following a similar motivation, Binder provides an updated framework for presenting heuristics by pairing a **context** in which the heuristic is applicable to a set of potential **actions** to be taken, similar to the example shown in Figure 2.1 [16]. This is the format used for presenting heuristics in this work, as understanding the proper contexts in which a heuristic should be used is a crucial first step in determining the value of a heuristic.



Figure 2.1 – Example Design Heuristic.

2.2 **Process Heuristics**

Process heuristics are those that guide the design process, rather than the direct design of the details of an artifact. For example, a process heuristic may be, "when aiming to generate novel systems concepts, consider using brainwriting." Brainwriting uses "naturally occurring ideas, without judgement, as starting points for concepts" [17]. Based on the definitions and characteristics previously presented, this is a process heuristic because the hypothetical designer understands when to implement the brainwriting technique as a guide towards a design solution. While brainwriting may not guarantee the

most valuable concept available, a designer may believe from experience that its implementation will generate at least one idea that will be considered satisfactory. Yilmaz et al. differentiate process heuristics from "local" or "transitional" heuristics to be those that define relationships in one concept or transform a current concept into a new concept [17]. An example of this is the "Substitute" heuristic – which may be written as, "when aiming to improve an artifact/system, consider substituting a design characteristic, such as material, with another that accomplishes the same function."

Barclay and Bunn define process heuristics as consistent with the editing stage of Kahneman and Tversky's prospect theory because they assist with "deciding how to decide" [18]. Prospect theory describes individual decision making in two phases: an editing phase and an evaluation-decision phase [19]. The editing phase manipulates prospects to simplify the evaluation-decision phase. Editing operations are meant to facilitate the task of decision making. An example process from Kahneman and Tversky is the *cancellation* operation, which tells the decision maker to discard components from the evaluation that are shared by all prospects. The *cancellation* operation may be considered a process heuristic in design because it guides the decision making process, rather than the selection of the details of an artifact.

When comparing the use of heuristics to the current idea of "rational" decision making, process heuristics should be included in the discussion. In normative decision making, the rational designer makes decisions that maximize the expected value of the design. Lee and Paredis show that value maximization must consider not only the outcome resulting from the use or sale of the artifact, but must also consider the cost of the resources needed to execute the corresponding design process in an organizational context [20]. Binder also discusses how heuristics outside of artifact heuristics affect the value of a product [16]. If it is desired to understand when to use heuristics in a way that maximizes the expected utility of design, it is beneficial to study process heuristics applied by designers in complex systems design.

2.3 Cognitive Bias

Cognitive bias has been studied in the fields of psychology and cognitive science, and can take many forms. From the perspective of human evolution and "adaptive rationality", researchers have divided cognitive biases into three types: heuristics, error management effects, and experimental artifacts [11, 21]. Adaptive rationality is based on the theory that the cognitive biases are derived from humans' evolutionary will to survive, and are not weaknesses or errors, but rather efficient adaptations of the mind to enable survival. Heuristics are rules of thumb used to save time and resources in exchange for satisfactory, but not necessarily optimal, solutions. Error management effects refer to humans making decisions toward less costly errors. Experimental artifacts are the result of research strategies or designs that place humans in unnatural settings or apply inappropriate norms [11, 21]. Haselton notes that these types are not mutually exclusive, as biases may fall into more than one category. Examples of these biases and their potential influence in design is shown in Table 2.1.

Cognitive Bias	Description	Potential Manifestation in Design Process
Endowment Effect / Ownership Bias [22-24]	Tendency to attribute increased value to an owned entity	• Bias toward concepts developed by oneself, when compared against those developed by others, leading to pursuit of concepts that may not ultimately be the best or may not surpass those already available to end users
Status Quo Bias [25-27]	Tendency to select a default option when one is present	 Bias to maintain status quo solution or similar, influencing benchmarking and ideation Bias toward initially generated concepts, and against iteration or further development of initial concept
Context- Dependent Preferences [28-30]	Tendency to change one's preferences based on context, including how many options are being compared and the nature of their comparison (joint or separate)	• Inconsistency in concept selection and comparison during benchmarking and ideation, in teams and individually
Availability [31, 32]	Making judgments based on the most available information in memory	 Misinformed perceptions of a market or problem space based on immediate association with that market Misinformed design decisions based on the most available user testing population
Effort Bias [31, 32]	A belief that the value of something is attached to the amount of effort put into it	 Continued pursuit of unviable concepts, due to large prior investment in development of those concepts Bias against fast prototyping for fast answers, against the mindset of "fail <i>fast</i>, fail early"

Table 2.1 – Examples of Potential Cognitive Biases in Design.

Table 2.1 Continued

Bandwagon Effect [33-36]	Tendency to support a decision without proof of its value	• Bias towards falling in line with the most popular design decisions rather than vocalizing opposition in a team setting
Confirmation Bias [32, 37- 39]	Tendency to seek out evidence, or interpret evidence in such a way, that is consistent with pre-existing beliefs, at the expense of considering belief inconsistent information	• Bias toward preconceived ideas of customer and market needs, toward previously held beliefs about design solutions and their potential for success
Hindsight Bias [31, 32, 40]	A belief that the outcome of an event was predictable or more likely, only after having knowledge of the outcome	• Bias towards a belief that unforeseen circumstances, such as negative user feedback or a missed latent customer need, should have been easily avoided.
Framing Bias [31, 32]	Allowing the frame (positive or negative) of a problem to influence decisions	 Design problem representation - how the problem is worded or perceived - could change the design decision making User feedback influenced by the way in which design concepts are presented to them

Error management biases decision making toward decisions that are less costly – from an evolutionary perspective, those that allow a greater chance of survival. Error management may increase overall error rates, but minimize fitness [11, 21]. In essence, the cost of false positive is much less than the cost of a false negative. When considering error management biases, be they optimistic or paranoid depending on the context, it's important to consider the evolutionary context to which they relate in order to hypothesize. In design

practice, error management may relate to things like self-preservation of one's livelihood or conservation of resources.

Experimental artifacts are biases that result from experimental design that compares human behavior to a "rational" or "optimal" choice that is not appropriate for the context, or uses a problem that is inappropriate within an evolutionary context [11, 21]. The key to reducing experimental artifacts is not necessarily changing the problem, but rather considering human decision making in the context of evolutionary survival, and relating the problem or context being examined to a more evolutionarily relevant situation. In many cases, apparently biased decisions become logical choices with this new lens. Experimental artifacts are considered in this proposed work as a caution in experimental design and results interpretation, rather than a crucial component of the taxonomy of biases.

When approaching the study of cognitive biases in design, it will be important not only to recognize when, where and how these biases manifest, but also the potential impact of the biases on the design outcomes – which may not necessarily be negative. While cognitive bias has been studied and documented thoroughly in the field of psychology and cognitive science, there is benefit to extension with engineering designers. First, engineering designers are a specific population that have been shown to differ from the general population, which may cause cognitive biases to manifest differently. For example, Williams et al. show that cognitive changes occur in students after design education experiences, including a change in focus of their design processes toward functionality [41]. In their training, engineering designers develop significantly improved spatial and visualization skills compared to the general public [42]. In addition, many cognitive differences between expert and novice designers have been found, which merit studies comparing the role of cognitive biases in these distinct populations [43]. Stanovich and West show that cognitive ability correlates with a tendency to avoid some cognitive biases [44], which may have implications for engineering designers, a more highly trained subset of the general population. Thus, these proposed studies are not replications of prior work, but expansions on the existing literature. Lastly, as discussed earlier in the experimental artifacts section, many studies have been performed in unnatural environments or using inappropriate norms of comparison. By studying engineering designers during the design process in situ, we can observe subjects in their natural working environment, and make sure to consider their cognition and decision making in the context of adaptive rationality [21]. By studying cognitive bias specifically within engineering design, the findings will be directly relevant and meaningful to design theory and practice – a valuable contribution to the state of knowledge in the field of design.

Cognitive bias in design has, thus far, been examined by only a few researchers, leaving much territory unexplored. Hallihan et al. focused on confirmation bias in the design process, first by establishing designer beliefs, and then looking for evidence of designers interpreting information to confirm their pre-existing beliefs. They found that most design teams studied displayed high levels of confirmation bias [32, 37]. Nelius and Matthiesen have used eye tracking to discover confirmation bias in engineering design, as well as a matrix method approach for debiasing [45, 46]. Viswanathan and Linsey [47] studied the link between fixation and the sunk cost effect, uncovering that sunk cost bias could be a major driver or cause of fixation during early stage design. They showed that

physical prototyping that requires more time and energy investment led to lower novelty and variety of ideas, and more fixation [47]. In the context of software designs with student populations, Parsons and Saunders found that anchoring can be observed when developers reuse code or prior designs, causing them to incorporate unnecessary functionality from the reused artifact or erroneous omissions of functionality following the reused artifact [48]. Zheng et al. found that concept selection was significantly impacted by the expectations that design students had for their concepts, indicating evidence of cognitive bias in early stage design decision making [49]. Choi et al. gives the bandwagon effect a positive spin, showing the benefits of bandwagon effect in recommender systems for movies, then applying this application towards the internet of things (IoT) [36]. Hindsight bias has been studied in relation to trust in automation, as well as foresight in complex systems and organizations [50, 51]. Mohanani et al. show several cognitive biases from a software engineering perspective, including confirmation, hindsight, framing, and availability bias [52].

In engineering design decision making, Vermillion et al. documented framing bias, showing that subjects were more likely to select the less risky option in positively framed scenarios but were risk neutral in negatively framed scenarios [53]. Toh et al. examined ownership bias and its relationship to gender, finding that male designers tended to exhibit ownership bias in concept selection, while women designers tended to exhibit the opposite bias (the Halo Effect) by selecting more ideas that were not their own [54]. Zheng and Miller followed this by showing that design professionals tend to choose their own ideas despite a lack of creativity and unfavorable rankings by team members [55]. Onarheim and

Christensen show how crowd-based decision making can overcome ownership bias [56]. Austin-Breneman et al. studied biased information passing among designers during negotiation in aerospace complex systems design processes. They found that sub-system designers would report conservative parameters or estimates with built-in margins to allow themselves room for design freedom when negotiating the design specifications with other sub-systems [57]. Effort bias has also been studied from the perspective of CAD systems and software development projects [58, 59].

2.4 Research Methods

A series of case studies were used to answer the research questions of this dissertation. Case studies investigate a *case* (individual or group) to answer research questions by extracting and combining a range of evidence within the case setting [60]. One key attribute of case studies is the ability to collect data using multiple methods: interviews, observations, document analysis, etc. The researcher then works *inductively* to develop theory that is grounded in evidence in the data. The qualitative data is often analyzed through *coding*, a process for discovering patterns in the data to be used for additional analysis [61]. One typical concern about case studies is their inability to be generalized. Creswell describes the case study as a "bounded system" – meaning the results are bounded by a particular time and place [62]. However, Yin argues that case studies, just like controlled experiments, are meant to expand and generalize theories over time [63].

It is easy to confuse case studies with other methods, such as an ethnography. In ethnography, the researcher is engaged with the daily activity of the subjects as a participant-observer for long periods of time [62]. The goal is to describe and interpret these activities, rather than to develop theory. Both methods require a more natural setting than a controlled experiment. Ethnographies have an intense study duration, lack of prior theory or hypotheses, and emphasis on observational evidence that separate them from case studies [63]. Ball and Ormerod address the complications of implementing ethnography into design research [64]. For example, it is often difficult to gain access into a designer's natural work environment for extensive periods of time as a participant-observer. Design studies also tend to have applied goals that aim to improve the design process, contrary to true ethnographies meant to simply describe but not modify the environment of focus.

Many studies of heuristics do not refer to themselves as case studies or any other type of study. Many of them can be assumed to be case studies by the method of data collection and the targeting of a specific group. For example, Yilmaz et al. focus their study specifically on products considered to be "innovative", while Bingham et al. interview only corporate executives in entrepreneurial firms [65, 66]. Previous case studies of heuristics have been broken into four main modes of data collection: 1) artifact analysis, 2) document analysis, 3) interviews and 4) surveys, each reviewed next.

2.4.1 Artifact Analysis

Overall, most case studies in design have relied on artifact analysis to infer how a designer uses heuristics to reach a final product [66-75]. An artifact is defined here as any

tangible object produced by humans or nature [76]. An artifact can be physically present or represented by sketches, photos, etc. The literature presented here contains a mix of studies that examined concept sketches, patents, and finished products.

The product analysis method used by Yilmaz et al. begins with identifying a set of products to be studied [66]. Heuristics are extracted by hypothesizing actions that led to identified features and elements. The reliability of these heuristics is presented through an inter-rater process of multiple coders. It is not meant to say these heuristics are the exact processes taken by each designer, but rather that it is possible to use the heuristics to reach similar results. The process used by Yilmaz et al. is similar to other studies identifying heuristics by patents or product analysis, although there are some variations. To identify environmentally conscious guidelines, Telenko and Seepersad add a life cycle analysis to existing products [67]. Singh adds a "deductive approach" by hypothesizing new situations in which design transformation is necessary, and for which heuristics can facilitate that innovation [68]. In each study, there is one clear theme – using a final product to hypothesize intermediate actions. Only one study identified obtained a sequence of sketches from an expert in industrial design, making it easier to see the designer's transitions from one idea to the next. [69].

Some studies are now turning to computer-based models for assistance with extracting or evaluating heuristics from artifacts. McComb et al. use hidden Markov models to identify heuristics through intermediate design actions [70]. A hidden Markov model is a two-stage stochastic process, which first describes state transitions within a discrete and finite state space, then generates outputs for every point in time [77]. The "hidden" descriptor is attached because the sequence of outputs is the only observable piece of the model's behavior. Matthews et al. also takes a computational approach to recognize patterns in existing solutions [71]. A verification stage uses experts to judge the accuracy, novelty, and importance of each heuristic per their own beliefs. Both models attempt to find the intermediate steps of a known final artifact. Binder, however, creates simulated artifacts and compares two different approaches for designing a pressure vessel: a heuristic approach and an optimization-based, expected-utility maximization approach [72].

2.4.2 Document Analysis

Identifying heuristics through document analysis is a method found in multiple studies [78-81]. For each document, a coding process is used to find patterns in the data, and these patterns become represented as heuristics for a domain. For example, Reap and Bras study prior literature to present guidelines for environmentally benign design and manufacturing (EBDM) [78]. Concepts coded were grouped into categories. The set of categories considered to be principles was reduced using criteria, such as "strong presence in literature" or "foundational importance in biology and ecology". The literature was then revisited to turn phrases into descriptive principles.

Many studies describe their own reasons for not implementing analysis of literature or similar records. Telenko and Seepersad decided against a literature analysis for environmentally conscious guidelines due to the risk of unforeseen tradeoffs and the possibility that they may not be applicable to current environmental issues [67]. Additionally, Bingham et al. believes document analysis lacks the insight into organizational processes necessary to fully describe a heuristic [65].

2.4.3 Interviews

Creswell presents interviews as advantageous when one cannot directly observe participants performing a task [82]. Participants can describe events in full detail, and the interviewer has some control over the information received, because they guide the conversation. Interviews can become disadvantageous if the interviewee begins to describe what they believe the researcher wants to hear instead of reality, or if there is difficulty in getting participants to open up, be clearer, and be articulate in responses. Once the interviews are transcribed and coded for themes, the participant's responses will be filtered through the eyes of the researcher. Studies that turned to interviews to examine heuristics typically followed the "semi-structured" format, using an initial predetermined set of questions, with room for follow-up questions throughout the interview [18, 65, 83, 84]. In these prior studies, heuristics were extracted by transcribing audio and coding the interview similar to the document analysis technique. One unique contribution from Bingham et al. related the use of process heuristics to better performance in organizational processes, although they did not present a full set of extracted heuristics [65].

2.4.4 Surveys

Surveys are a relatively inexpensive form of data collection that can reach a diverse population in a short period of time [82]. Surveys mostly use closed-ended questions in which participants choose among a given set of responses. Open-ended questions do not constrain responses, but they do require coding the data for themes as part of the analysis. Many surveys combine both methods by giving participants a set of responses, along with the option to write-in an alternative response if the given responses are not sufficient. The most noteworthy flaw with survey data is that it is self-reported data. The data may only confirm what people think and not necessarily what they do. Surveys may also be blind to outside variables that contribute to correlations found in the survey data. With respect to the survey design, Creswell lists ten common issues to be avoided, shown in Table 2.2 [82]. Only one study was found to use surveys as a primary method for extraction and verification of heuristics by using the Delphi method [85]. Experts were sent a predetermined set of heuristics and asked to rate each heuristic according to its relevance in computer-supported collaborative work (CSCW). The survey gave the option of adding new heuristics to the set as well. There were 3 rounds of surveys, with the surveys edited based on previous ratings and additions. The end product was a set of heuristics meeting the threshold of relevance for collaborative creativity.

Ten Common Mistakes to Avoid		
The question is unclear.	There are overlapping responses.	
There are multiple questions within a question.	There are unbalanced response options.	
The question is too wordy.	The question and answers are mismatched.	
The question is negatively worded.	The questions are overly technical.	
The question includes jargon.	The questions do not apply to all participants.	

Table 2.2 – Common Su	rvev Issues	to Avoid
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The background section provided an overview of how heuristics have been viewed historically, as well as different forms of heuristics, such as process heuristics. It presented the idea of heuristics framed as a cognitive bias, and it also presented many prior research methods associated with heuristics which will inform our methods approach to studying heuristics. This background knowledge will be the basis for attacking the following research questions:

1) How should the methodology for extracting heuristics be improved such that we may assess the value a heuristic brings to the design process?

2) What aspects of heuristics and design environments should be considered during documentation of heuristics in a repository?

3) How might heuristics be characterized and classified to understand their impact on design processes?

An understanding of what has been done before this dissertation is critical to understanding the ways in which the following chapters contribute to design methodology for heuristics. The methodology will influence the magnitude and type of information extracted from participants to address repository considerations. Lastly, understanding that heuristics have different intentions (i.e., artifact focused versus process focused) and different perspectives (i.e., from a cognitive bias perspective) will influence how heuristics might be characterized or classified. The following chapter will take this background knowledge and apply it to extracting and characterizing heuristics from a group of designers at Jet Propulsion Lab.

CHAPTER 3. CHARACTERIZATION OF HEURISTICS IN JET PROPULSION LAB'S ARCHITECTURE TEAM (STUDY I)

3.1 Research Objectives

The focus of Study I is based on the following research objectives:

1. To understand how expert designers use design heuristics.

Understanding the role of heuristics in expert design practice will allow us to assess how heuristics are helping or hurting the design process, and how a tool used to aid heuristics use would best be implemented into a designer's current mental and physical processes. With the overarching goal of adding value to the way in which design is done, the value of how heuristics are currently being used can be identified, along with areas for improvement.

2. To develop a repeatable method for extracting valid heuristics from designers.

Currently, a method doesn't exist that confirms the heuristics with the designers after they have been extracted. With the goal of advancing design science methods for heuristics, if heuristics can be repeatably and consistently extracted, they can then be documented, studied, and presented to others.

3. To provide insight into how heuristics can be characterized and classified so that we may understand how they bring value to the design process.

The characterization of heuristics drives toward the goal of a normative approach to heuristics use in design. In characterizing the value of heuristics, we can begin to recommend when or how one is better than another, pushing forward a prescriptive design process support system. Classification enables heuristics to be grouped based on a multitude of attributes within a repository, and thus allows for them to be queried, explored, and presented based on context of applicability. A heuristic is only useful when the context matches that at hand.

3.2 Participants

The participants of this study were engineers associated with JPL's A-Team. JPL is one of NASA's federally funded research and development centers [86]. They not only implement space science missions but also provide mission formulation support to many clients. Increased competition, complex mission ideas, and strict technical evaluation standards have led to more emphasis on mission formulation processes in recent years. The JPL Innovation Foundry was created in 2005 to address formulation issues. The A-Team is a newer component of the Foundry and was formed in 2011. For all clients, The Foundry aims to evolve ideas into resilient concepts and provide accurate forecasting despite incomplete data. Clients are provided guidance for decisions such as performance, risk, and cost through access to subject matter experts (SMEs) and previously completed missions. Overall, four main initiatives have been developed within the Foundry to improve formulation processes: Team X, Team X_c, A-Team, and the Proposal Center. To assist the formulation process, a Concept Maturity Level (CML) scale was created to consistently ascertain a mission concept's maturity, as shown in Figure 3.1.



Figure 3.1 – Concept Maturity Levels developed by Jet Propulsion Lab.

The CML scale measures the maturity of deep space mission concepts [86]. Until the CML scale was developed, NASA had no standards for measuring concept maturity or comparing concepts during early formulation. CML is analogous to the Technology Readiness Level (TRL) scale already in place to describe the maturity of a proposed new technology [87, 88]. CML allows engineers to better understand assumptions and potential flaws that form during concept formulation. Standards for concepts at each CML may be found in more detail in the CML Matrix [86, 87, 89]. This tool benchmarks each CML stage based on key technical and programmatic elements identified by JPL. This study focused mainly on the A-Team and CML phases 1-3. CML 1 presents the very core idea of a mission concept [87]. This usually includes high-level objectives, science questions, the science for addressing those questions, and a "cocktail napkin" sketch of the mission concept [89]. In CML 2, ideas are expanded and assessed based on analogies for feasibility from science, technical, and programmatic perspectives. Basic calculations are performed,

and key performance parameters are quantified. A feasible concept then moves to CML 3, which considers a broad trade space around a reference design point [87]. The trade study explores impacts on science return, cost, and risk [89].

The A-Team exists to move concepts through CML 1-3 and has performed over 250 studies since its founding in 2011. A-Team clients include principal investigators, internal project or program managers, and sponsored external clients, among many others [90]. An entire A-Team study lasts about 6 weeks, beginning with client meetings [91]. Background information, goals, and requirements for the study are discussed at length during the client meeting [90]. The A-Team Study Lead then collaborates with the Client Lead to create a study plan. The study plan is reviewed and agreed upon at a planning meeting.

The official A-Team study is conducted in half-day segments and usually lasts one full day [91]. Studies take place in a designated area named 'left field', filled with reference material and whiteboards to promote creativity [92]. There are 8-12 people in each study including the facilitator, study lead, assistant study lead, documentarian, and subject matter experts asked to participate based on the study objectives and scope [92]. Sometimes, the facilitator may be the study lead [90]. Numbers are kept intentionally small to ensure active discussion and high productivity. Every person in the room is expected to participate. The facilitator is responsible for carrying out scheduled activities, typically beginning with presentations to introduce the client's problem and the state of the art [92]. This leads into segments for idea generation and concept selection, usually through voting. For the remainder of the study, selected concepts are evaluated as potential solutions for the client. All documentation of the study, from the study plan to the results, is contained in a wiki accessible by A-Team members and clients. For mission concepts to be further developed, future steps would pass formulation along to Team X for a matured point design.

The A-Team was an appropriate subject pool for this study due to the large presence of heuristics during A-Team studies. Decisions are made during mission formulation despite a lack of critical information [86]. To make these decisions, subject matter experts rely on heuristics formed from past experiences and intuition. Process heuristics are used for in-study analyses. Planning heuristics are necessary for deciding the experts, tools, and other resources necessary to meet the client's objectives. They determine agenda items as well as the time budgeted for each item. Our study identified and characterized these heuristics through the use of interviews and surveys. In selecting the A-Team as the case for this study, the researchers argue that they are an exemplary case, rather than extreme. Mills et al. define extreme cases as trying to "highlight the most unusual variation in the phenomena under investigation, rather than trying to sell something typical or average about the population in question [93]." Additionally, example cases are used when "the relationships observed in that particular case may generalize to other cases to the extent that they, like the exemplar, possess the features that define class membership [93]." Some may consider the composition of the A-Team to be an "extreme" case, as the members have a significantly higher level of knowledge and education than the average person; however, within the context of this type of center or company at the leading edge of a technological field, this team composition is not uncommon. Studies with other design teams (within or outside of space mission design) will yield not an identical set of heuristics, but similar types of heuristics.

3.3 Methodology

The goal of this study was to extract heuristics used in the A-Team setting at JPL using interviews as the primary method for gathering data. The study was purely voluntary with no form of compensation. The interviewer was one graduate researcher, assisted by two undergraduate transcribers/note takers. For in-person interviews, a faculty observer was present. The ten participants interviewed average sixteen years of engineering experience, ten years of design experience, 12 years of JPL experience, and 29 A-Team studies. There were nine white men and one white woman interviewed. Three participants were between 21-30 years old, three between 31-40 years old, three between 51-60 years old, and one between 61-70 years old. Six participants were systems engineers, and the other four participants held management positions.

A-Team members who agreed to participate in the study were contacted by email to determine interview logistics. Availability and scheduling conflicts led to differences in time of day and interview settings over a span of six months. Five out of ten total interviews were conducted by phone, and the remaining five were given in-person using conference rooms at the Jet Propulsion Lab. All interviews followed the same semi-structured format to maintain consistency in data collection. Interviews lasted approximately one hour each and were conducted by one researcher while two additional researchers observed and took notes by hand. Researchers conducting interviews had no prior relationship with JPL. Interviews were audio recorded for future transcription and heuristic extraction. Interviews were semi-structured with a script, allowing for follow-up questions when necessary. The interview format guides the participant through three main sections: forming an understanding of heuristics, generating heuristics used in an A-Team setting, and characterizing the heuristics identified. The semi-structured interview script was subjected to an expert review and piloted with a graduate design researcher. The questions were found to be clear and unbiased, in their opinion. No changes were made to the content or structure of the interview script after the pilot. The script can be found in Appendix A.

3.3.1 Part 1: Understanding Heuristics

In the first 10-15 minutes of the interview, participants spoke on their official and unofficial roles at JPL and within the A-Team. The researcher then gave an overview of the study and moved into a discussion focused on heuristics. Participants received a detailed definition of heuristics along with relevant examples of heuristics that engineers at JPL may potentially encounter. Prior to the interviews, the researchers gathered a broad range of example heuristics in spacecraft design from *Space Mission Analysis and Design* [94] to prevent fixation on a particular mission area or spacecraft subsystem. The goal was to help the participants to recognize that heuristics exist across all areas and aspects of the design process; if they stay fixated on planning or thermodynamics, they may be missing some key heuristics they use during the A-Team studies that may not cross their minds. However, the number of examples presented varied based on the participant's understanding of heuristics. Some example heuristics used are shown in Table 3.1.

Context	Action	
If the mission is to an outer planet	Use a nuclear power source	
When designing a small satellite to be earth-oriented	Use a gravity gradient technique for guidance and control	
For spacecraft design and sizing	First start by preparing a list of design requirements and constraints	

Table 3.1 – Example Heuristics Used for Interviews.

3.3.2 Part 2: Generating Heuristics

Once participants became more familiar with heuristics, they attempted to state as many heuristics as possible that they use in their own designs, particularly within the A-Team. Participants were given 30-35 minutes for heuristic articulation. The researcher asked follow-up questions as necessary to prompt the participant to express these heuristics in the desired "context - action" form. If the participant struggled to identify examples of heuristics in their own work, they were presented additional examples of heuristics for assistance. In many instances, the participant would state the heuristic as "context-action" without assistance from the researcher. In identifying heuristics, participants were not limited to any particular type of design (new design vs. redesign), phase of the design process, or area of application. Some example excerpts from the interview transcripts are presented next.

Participant G: "If you just want feasibility of a mission, you generally want to look at multiple concepts, because even though one of them might look good initially, it might fall through."

Extracted Heuristic: "For a study to determine the feasibility of a mission, look at multiple concepts."

In this case, the participant clearly expressed the contextual situation and a recommended action to take. In the context of determining a mission's feasibility, the suggested process is to look at multiple concepts rather than just one.

In other cases, a process would be discussed in detail, and then the researcher and participant collectively agreed upon the heuristic in "context-action" form:

Participant H: "Often we'll have an exercise just to think about the figures of merit, then we ask the participants to keep them in mind as they are doing the multi-voting exercise. Instead of actually applying the figures of merit, we are priming them with what we hope they will make their selections on. That seems to be the less time constrained version of it, rather than saying if a concept is high, medium, or low on all these figures of merit. It could become very time consuming."

Researcher: "So, when you are multi-voting, keep in mind the figures of merit."

Participant H: "Yes, that's usually the more effective approach for time purposes."

Extracted Heuristic: "When multi-voting, consider how the concepts relate to each figure of merit."

Some heuristics were not immediately placed into context-action form due to the nature of some conversations. In these cases, the researcher used transcriptions to locate the context and action of the heuristic being discussed:

Participant D: "...and we have about sixteen people in the A-Team. Only two are full time, as I said, and we like studies to have between eight and twelve folks. When you get less than eight you probably don't have diverse enough opinions to brainstorm and get the ideas all over the place, and if you get more than eighteen people, twenty people it is really tough to control."

Extracted Heuristic: "When planning an A-Team study, design the study to have between 8-12 people."

After interviews were transcribed, qualitative analysis began through the interviewer identifying the action that the interviewee was suggesting be taken, and then found the corresponding context that was stated for that action. There was no interpretation of the transcript that occurred – the interviewer directly transcribed the context and actions that they explicitly referred to. Two researcher assistants coded two of the ten interviews to extract context and actions for each heuristic discussed. The interviewer independently coded these same interviews, and compared for accuracy. Comparing between the raters, the extracted heuristics were consistent. Any differences were semantic in nature.

3.3.3 Part 3: Characterizing Heuristics

For the final 10-15 minutes of the interview, participants spoke on how they first encountered these heuristics. Then one heuristic was picked that participants felt most comfortable discussing in more detail. For this heuristic, many questions were asked to get the participants thinking about characterizing heuristics with a focus on justifying the action taken. For example, researchers asked how often the heuristic was applied, how often the heuristic was updated or "evolved", and how reliable the heuristic seemed to be for helping the designer to reach a satisfactory solution.

As soon as a set of heuristics were documented from the interview, a survey was distributed via email to obtain more information about each heuristic. The survey was estimated to take ten minutes to complete. Surveys were not piloted. Surveys were reviewed for clarity and leading questions/bias by multiple expert level faculty researchers on the team. We used this approach for validity checking, as we had a tight turn around between when we interviewed the participants and when we needed to follow up with the survey so that the content was still fresh in their minds. The overall structure of the survey and framing of the questions was vetted by the research team, and then extracted heuristics from each individual were inserted into the identical survey structure for all participants.

The first part of the survey obtained demographic information, and the second half asks for additional characterization of the documented heuristics. Questions were similar to many interview questions but were not open ended. Surveys were modified such that participants characterized their own heuristics only and not the entire set of data. Characteristics obtained through survey questions include: **Source/Origin:** Sources hypothesized by the researchers were placed in the survey, but the participant also had the choice of writing any source not listed.

Applicable Concept Maturity Levels: Participants selected the CML stage(s) where the heuristic is applicable. A "not sure" option was also provided.

Number of Years Used: Participants identify how many years they have been using the heuristic by selecting from various ranges provided.

Frequency of Use, Reliability, Evolution: Participants self-assessed how often they use a heuristic, how reliable that heuristic is to reach a satisfactory solution, and how often the heuristic evolves or tends to be updated. These attributes were graded on Likert scales ranging from 'never' to 'always', including a "not sure" option.

3.4 Results and Analysis

From the ten interviews, 101 heuristics were identified. This total does not consolidate any heuristics that appear to be repeated across multiple participants. For example, multiple participants discussed the delta-v thresholds at which they would consider electric propulsion. Keeping these separate allowed each designer to fill out the survey based on how they perceive the heuristic. There were also heuristics containing the same action for different contexts. For example, using previous designs as a starting point for a new mission is beneficial from the context of determining feasibility, reducing cost and addressing risks. The total set of heuristics can be found in Appendix B.

There was a clear difference between the quantity of heuristics extracted from phone interviews compared to in-person interviews. Phone interviews averaged 12.6 heuristics per person (sixty-three total), and in-person interviews averaged 7.6 heuristics per person (thirty-eight total). In general, in-person interviews seemed to produce more

engaging conversations that discussed heuristics in greater detail. Consequently, it also led to fewer heuristics discussed throughout the course of the interview. Although phone interviews produced a higher quantity, both environments were effective in identifying the heuristics the participants contribute to A-Team studies. The total number of heuristics identified by each participant is shown below in Table 3.2.

Participant	Number of Heuristics	Interview Type	
А	11	Phone	
В	8	Phone	
С	15	Phone	
D	18	Phone	
Е	Excluded (did not complete survey)	Phone	
F	11	Phone	
G	9	In-Person	
Н	10	In-Person	
Ι	7	In-Person	
J	9	In-Person	
K	3	In-Person	

Table 3.2 – Quantity of Heuristics by Participant.

3.4.1 Classification

A classification was created to reduce designer search and analysis time by limiting the heuristics presented during decision making to those immediately related to the context. The classification scheme developed is shown in Appendix C. The classification is broken into three levels: primary area of concern, secondary area of concern, and action intent. Heuristics are labeled using one category per level for a total of three categories. In Appendix C, the number of heuristics associated with each category is presented in parentheses.

Categories were created by blending identified themes and relationships across heuristics, with inspiration from reference materials. For example, consider the three primary areas of concern: A-Team study design, mission design, and spacecraft design. All three categories are based on emerging themes from the data. Secondary areas of concern for A-Team planning are also based on data trends. However, secondary areas of concern for mission design and spacecraft design were developed by blending Fortescue's spacecraft mission objectives and requirements with trends in the extracted applicability contexts [95]. Action intent uses similarities in suggested actions from the data, and draws on our previous work using design phases from Pahl & Beitz [96, 97].

Some secondary areas of concern, such as planetary protection, were kept in the final classification despite having a small amount of heuristics due to their importance to JPL's own design processes. On this note, Innovation Foundry research literature was also used as inspiration for categorization [86, 87]. In future work, all categories have potential to expand, and new categories have potential to emerge.

In comparison to previous literature, our classification differs in the purpose for which it was developed. Two previous studies began with a clear understanding of the designer's intent. Daly et al. studied designers who intend to generate ideas, and Telenko et al. studied designers who intend to design with consideration of the environment [81, 98]. The classifications that followed were designed to describe how these goals are achieved. For example, Daly et al. showed how transitional heuristics generate ideas by building off existing concepts. The classification in this study has a different purpose due to the unconstrained scope of heuristics in the interviews. The classification starts at a higher level in the design process and ends with the designer's intent, a region similar to where the classifications of other studies begin. The reasoning for this classification is to reduce the broad set of heuristics into a smaller set that allows for a feasible comparison of decision alternatives.

3.4.2 Survey Results

The survey results and analysis are presented in Figures 3.2-11 and give insight into potential characterization and evaluation of heuristics. It is worth noting that nine heuristics had a lack of insightful data across each of our four main questions; they were labeled as no frequency of use, no years used, and were unsure about evolution and reliability. These heuristics were kept in results for specific survey questions, but were removed from analysis when comparing data across survey questions. Understanding why participants were not able to articulate more about these heuristics would be of high importance in future work.

Statistical analysis was performed on the three primary categories of heuristics, as presented in the classification subsection: A-Team Study design, Mission Design, and Spacecraft Design. The nonparametric Kruskal-Wallis H Tests were performed to determine differences in frequency of use, years used, and participant years design experience across the three primary groups. Although design experience is a continuous variable, outliers were found in the data by inspection of a boxplot, which prevents the use of a one-way ANOVA test. For each analysis, distributions of scores were not similar for all primary categories, as assessed by visual inspection of a boxplot. As a result, the Kruskal-Wallis test may only use mean ranks to tell us whether a group had higher or lower scores than another group, but may not specify the size of the difference. If significance was found, pairwise comparisons were performed using a Bonferroni correction for multiple comparisons. Adjusted *p*-values are presented, and values are mean ranks unless otherwise stated.

The distributions of frequency of use scores were statistically significantly different between primary concern groups, H(2) = 11.922, p = .003. The post hoc analysis revealed statistically significantly higher frequency of use scores for A-Team Study Design heuristics (58.81) when compared to Mission Design heuristics (36.47) (p = .002). This is logical in the sense that A-Team studies will always require planning heuristics before the study and process heuristics during the study. On the other hand, studies begin at a variety of CML stages, and the maturity level may call for exclusion of some mission design heuristics.

The distributions of Years Used scores were statistically significantly different between primary concern groups, H(2) = 17.443, p < .001. The post hoc analysis revealed statistically significantly higher scores for Spacecraft Design heuristics (59.03) compared to both Mission Design heuristics (43.02)(p = .033) and A-Team Study Design heuristics (32.56) (p < .001). As spacecraft design heuristics are typically those that a subject matter expert may bring to the study, it is reasonable that they have been tested more over the years. Additionally, as the scope of missions change, and as the A-Team modifies it process to be more efficient, these heuristics are likely to change as well without being used for a high number of years. The A-Team being a relatively new group to JPL may also play a factor.

The distributions of Years Design Experience were statistically significantly different between primary concern groups, H(2) = 17.799, p < .001. The post hoc analysis revealed statistically significantly lower years of design experience for the A-Team Study Design heuristics (28.73) compared to both Mission Design heuristics (49.16)(p = .013)

and Spacecraft Design heuristics (56.91) (p < .001). It is possible that less experienced designers have not been exposed to enough variety in missions to have developed their own mission design or spacecraft design heuristics. On the other hand, less experienced designers are also more likely to be systems engineers who are seeing more of the A-Team development in action, as shown in Table 3.3. Therefore, A-Team design heuristics may have just been the most available strategies in mind at the time of interview.

	Systems Engineers	Management Positions
Total Participants	6	4
Mean Years Design Experience	5.17	16.75
Median Years Design Experience	3.5	16

Table 3.3 – Breakdown of Experience by Job Title.

Figure 3.2 shows that a clear majority of heuristics identified were self-reported as gathered from experience, which follows our expectations based on the definition of a heuristic. Heuristics gained from colleagues and A-Team studies tied for the second most generated responses. Participants could choose as many sources as necessary to describe the origin of the heuristic. For example, a heuristic obtained from a colleague within an A-Team study may fall under both categories. It is important to note that rules of thumb are not only picked up through a designer's own experiences but the experiences of others as well. These are obtained by observing colleagues in a design situation or having them explicitly stated in a form of mentoring. Heuristics self-reported as picked up during A-Team studies may include planning heuristics specific to the A-Team or heuristics that participants have noticed other members use during a study. Outside of the A-Team, a designer having direct access to the heuristics of colleagues or mentors is one benefit of a

heuristic database. Designers may also understand how their own heuristics are influenced by personal design experiences compared to learning from others over time.



Sources of Heuristics

Figure 3.2 – Origin / Source of Heuristics.

The nonparametric Mann-Whitney U tests were run to determine any differences in frequency of use, years used, and years of design experience in relation to originating sources. Although years of design experience is continuous data, an ANOVA was not used due to violations of normality. Distributions between groups for each source were not similar, as assessed by visual inspections. This means the Mann-Whitney U test results will show any significant differences in scores based on mean ranks. There were no statistically significant differences when comparing frequency of use scores to originating sources.

Significant differences in years of design experience were found within one of the sources tested: A-Team Studies. Results show that years design experience for participants that generated heuristics originating from A-Team (mean rank = 29.58) were significantly lower than the years of design experience for participants that generated heuristics not from

the A-Team (mean rank = 58.95), U = 373.5, z = -5.271, p < 0.001. Figure 3.3, which compares originating sources by design experience, shows an overwhelming number of heuristics discovered within the A-Team as generated by participants with less than ten years of experience (six out of ten participants). As the A-Team was formed in 2011, it is clear that less experienced designers would pick up and develop their own heuristics in the A-Team environment, whereas more experienced designers may have first formed these heuristics in other environments.



Figure 3.3 – Heuristic Sources Compared by Participant Design Experience.

Statistically significant differences in Years Used scores were found in four of the sources tested: Textbook, Education, Experience, and Colleagues. For each source, results show that heuristics originating from that source had significantly higher Years Used scores than heuristics not originating from that source. For example, results show that Years Used for heuristics originating from Textbooks (mean rank = 63.05) were significantly higher than Years Used for heuristics not originating from the results not originating from Textbooks (mean rank = 63.05) were

rank = 41.90), U = 1051, z = 3.299, p = 0.001. Similar results from Education, Experience, and Colleagues are found in Table 3.4.

	Mea	n Rank	Mann-	Standard Test	Significance
Source	From	Not From	Whitney U	Statistic (z)	(p)
	Source	Source			
Textbook	63.05	41.90	1051	3.299	0.001
Experience	51.32	36.53	1229	2.622	0.009
Education	59.48	40.82	1259	3.248	0.001
Colleague	57.20	37.90	1484	3.627	0.001

Table 3.4 – Mann-Whitney U Results for Years Used vs Heuristic Source.

A possible explanation for the above results is that the longer a heuristic has been used, the user has more likely seen it arise from multiple sources. As shown in Figure 3.4, 36% heuristics were assigned just one originating source, 31% had two sources, and 29% were said to have been identified in more than two sources. This explanation is supported by a Spearman's correlation showing that Years Used has a positive, linear relationship with the number of sources selected for the heuristic (Spearman's = 0.382, p < 0.001, N = 92). A closer look at heuristics with multiple sources showed that pairing these four sources together (textbook, experience, education, colleague) produced 6 of the 8 most frequent source pairings for heuristics, as shown in Table 3.5. Therefore, it makes sense that these are the four sources to have been significant. The sources "JPL Standard" and "Mentor" likely were not associated with enough heuristics to obtain significance.



Figure 3.4 – Number of Originating Sources Selected for a Heuristic.

Combinations	Total
Experience + Colleague	29
Experience + A-Team	23
Colleague + A-Team	22
Experience + Education	18
Experience + Textbook	16
Education + Textbook	15
Colleague + Textbook	15
Education + Colleague	15

Table 3.5 – Most Frequent Combinations of Sources for Heuristics.

Figures 3.5-6 refer to the self-reported applicability of the heuristics in relation to concept maturity levels. The A-Team performs studies through CML 1-3, so it is understandable that the majority of heuristics are applicable at those levels. Most of these heuristics can be used across all three CML stages, or at least 2 of the 3. However, at some point the design becomes too mature for the heuristic to be used. In other words, the heuristic loses its value as the designer progresses through the design process. For A-Team

members, the set of heuristics considered can be reduced by knowing the value a heuristic carries to a CML stage. Outside of the A-Team, this idea can be modified to fit design processes to assess value across design phases.



Applicable CML Stage

Figure 3.5 – Applicable CML Stage for Heuristics.



Frequency of CML Stage Pairings

Figure 3.6 – Most Common CML Pairings for a Heuristic.

Figure 3.7 shows that the heuristics identified have been self-reported as most commonly been used for 2-5 years. This may reflect a number of factors including the youth of the A-Team, which has only existed since 2011. Any heuristics picked up from inside the A-Team studies would not likely be more than 5 years old. They may represent each participant's own design experience, and some may describe the timeline for heuristics becoming obsolete and replaced with new heuristics. Outside of the A-Team, this data could be used to represent reliability or evolution as a function of time or identify when it is time to update a heuristic. More information would be required to determine the effect any of these hypothesized factors have on the data. This is discussed further in the "Conclusions" section.



"How long have you been using this heuristic?"

Figure 3.7 – How Long Each Heuristic Has Been in Use.

Figure 3.8 shows self-reported data for how frequently the designer uses each heuristic, along with its reliability and tendency to evolve. Most heuristics were described as being used in most or all design problems encountered. This may be due to the designer

frequently encountering problems of a similar domain, or the heuristics that came to mind during the interview were simply the ones used most often.



Figure 3.8 – Self-Reported Evaluations of Heuristics.

For reliability, most heuristics were self-reported as "frequently reliable" and no heuristics were considered "never reliable". Because heuristics are trusted to lead to satisfactory solutions, it is understandable that the designer perceives their own heuristics to be fairly reliable. Some heuristics were listed as "always reliable". This is less common due to the importance of the context - most heuristics are not universally relevant or applicable. For this study, some heuristics may be always reliable because advancements in science and technology are required to offer better alternatives. For example, consider the heuristic, "When choosing the power source, incorporate only one source on the spacecraft due to costs." Power has likely been too expensive historically to afford multiple sources for a spacecraft. Therefore, until advances are made to drastically reduce cost, it is not worth the time and resources to consider mission performance when multiple power sources are involved.

For evolution, most heuristics were considered "rarely or never evolving". This means the designer rarely has to modify the heuristic to maintain its value. If a heuristic constantly required evaluation and modification, it would lose its ability to save time and resources. Therefore, it makes sense that the heuristics were rarely judged as "always evolving". Outside of the A-Team, all of these characteristics may allow designers to assess the value of one heuristic compared to another. The designer may also have a better understanding of how and why pieces of their own design methods change or stay the same over time.

The combination of self-reported survey responses for evolution, reliability, and frequency were tested for correlations using Spearman's rank correlation coefficient, more commonly known as Spearman's rho. This was used instead of a parametric test because the data was ordinal, which makes a Pearson's correlation inappropriate [99]. Results from a Spearman's correlation test can provide information regarding the strength and direction of a monotonic relationship regarding two variables. All statistical analyses were done using the IBM SPSS statistics software package. Any survey question receiving a "not sure" was deleted from the analysis because it does not fall along the ordinal scale of the other responses.

The combination of survey responses for frequency of use and reliability of a heuristic are shown in Figure 3.9. A Spearman's correlation coefficient of 0.305 shows this relationship has a positive correlation. This means when the heuristic is used more frequently, the reliability tends to increase. This correlation has 2-tailed significance at the 0.01 level with a sample size of 86. This relationship makes sense because designers will

use a rule of thumb more often if it continues to bring consistent results. On the other hand, a heuristic with inconsistent results is less likely to be retained by the designer. Examples of heuristics on each end of the scale are presented below.

Low frequency of use, low reliability: "When creating schedule reserves, allot more time for later project phases."

High frequency of use, high reliability: "When planning an A-Team session, design the study to have between 8-12 people."

The scheduling process shown in the first example may not account for enough variables to be successful across a wide range of studies. For the second heuristic, the A-Team may have noticed over time that teams of 8-12 people delivered the most successful studies.

Figure 3.10 shows combined survey responses for frequency of use and evolution of a heuristic. A Spearman's correlation coefficient of -0.385 shows this relationship has a negative correlation. This means a heuristic used more often also tends to evolve less often. This correlation has 2-tailed significance at the 0.01 level with a sample size of 75. It makes sense a heuristic is used more if it requires less analysis and updates. If the designer wants a "quick and dirty" method to move through the decision process, actions that do not require constant evaluation are more preferred. Repeated updates and analysis defeats one purpose of the heuristic itself, to save processing time. Examples of heuristics on each end of the scale are presented below.

Low frequency of use, high evolution: "During the client meeting, determine if homework is necessary for the study, so you can estimate the session length."

High frequency of use, low evolution: "For a study with a very high number of participants, break into groups for brainstorming."

For the first example, "homework" may not be easily determined in the client meeting, or there may be other factors affecting session length valuable to identify. The second example may be effective at keeping large groups productive regardless of the study topic.

Figure 3.11 shows combined survey responses for reliability and evolution of a heuristic. A Spearman's correlation coefficient of -0.435 shows this relationship has a negative correlation. This means a more reliable heuristic tends to evolve less often. This correlation has 2-tailed significance at the 0.01 level with a sample size of 72. A heuristic not properly updated is more likely to be misused, so heuristics requiring less updates will be more reliable over time. Overall, the correlations presented so far suggest that for reliable success, a heuristic should be broadly applicable for more frequent use and not changing over time for less evolution. Examples of heuristics on each end of the scale are presented below.

Low reliability, high evolution: "When designing a spacecraft, estimate your electrical system to be between X-Y% of the spacecraft mass."

High reliability, low evolution: "When choosing the power source, choose based on the mission location."

The mass percentages for a spacecraft may fluctuate with factors such as evolving costs and technologies or the purpose of the spacecraft. However, choosing a power source based on mission location is a reliable process because the power source largely depends on the available sunlight. Of course, explanations of survey responses for each example are speculative and not supported by data.



Figure 3.9 – Self Reported Combinations for Frequency and Reliability.



Figure 3.10 – Self Reported Combinations for Frequency and Evolution.



Figure 3.11 – Self Reported Combinations for Reliability and Evolution.

It is not likely that designers consciously think through characteristics such as these when applying heuristics. Understanding the impact of these correlations can aid the designers thought processes during decision making. Designers may begin to actively recognize when a heuristic has lost its value and must adapt to stay relevant. These results rely on self-reported data and may contain bias for how participants judge their own design actions. If designers are overconfident when self-assessing the reliability of a heuristic, it can lead to erroneous decision making. However, these are the first results known to connect a designer's heuristics to a set of variables and attempt to understand how design heuristics change over time.

During the interviews, most participants expressed heuristics alongside an example study of when the heuristic was implemented. Interview transcripts also revealed that the A-Team generalizes each study into one of four study types: architecture, technology, science, and strategy studies. Based on the interview data, improvements to this study can begin obtaining the applicability of each heuristic based on the four study types. For classification purposes, this could create a 4 x 3 matrix in which each study type and concept maturity level provides a set of applicable heuristics. For the attributes, it provides an opportunity to see how the value of a heuristic changes as the study type changes.

Additionally, the interviews revealed that many heuristics were presented with an underlying intention of reducing costs or risks. For example, a heuristic for choosing solar power as the power source is based largely on the desire to reduce costs otherwise associated with nuclear power. Connecting a designer's value of cost and risk with the emphasis heuristics place on cost and risk could improve the value measure for a heuristic in certain contexts. It could also provide an additional level of division between heuristics considered, similar to how Moe et al. divide actions based on cost and scheduling constraints [100].

3.5 Conclusion

In this study, interviews were used to extract heuristics applied during JPL's A-Team studies for formulation stage mission design. Heuristics were extracted to include a context in which the heuristic is applicable followed by a suggested action to take. A classification was formed to allow designers to focus on heuristics applicable to their current design context. Surveys obtained attributes of each heuristic that may guide the designer in choosing one heuristic over others in the same applicability set. Statistically significant correlations between frequency of use, evolution, and reliability of a heuristic are presented as a starting point for understanding relationships between the attributes of a heuristic. A positive correlation was found between frequency of use and reliability, while negative correlations were found between frequency of use and evolution, and reliability and evolution. This study presents heuristics as reported by the participants and does not intend to recommend using the set of heuristics or guarantee successful application. To return to the originally outlined research objectives, each objective and how it has been addressed is discussed next.

1. To understand how expert designers use design heuristics.

- The results indicate that many heuristics can be identified and articulated by designers, and they are consciously used during the design process.
- Results indicate that heuristics come from a variety of sources, and are not limited to personal experience.
- The extracted heuristics were reported to be used in different phases of the design process, with applicability to different subsystems and with a variety of action intents.

2. To develop a repeatable method for extracting valid heuristics from designers.

- Semi-structured interviews can be used to extract heuristics from designers. Surveys based on those heuristics can collect designer characterizations of their own heuristics. This method allows for designers to articulate and confirm the use of their heuristics, rather than researchers deducing them from design observation alone.
- This method was useful for identifying a broader range of heuristics than protocol and product analysis due to the ability to discuss the designer's full process with them. With the ability to direct or draw attention to all parts of the design process, this method expands the scope of heuristics one can extract.

 This method does not yield unconscious heuristics – heuristics that designers are not aware that they use or know. A hybrid method combining direct observation (such as protocol or product analysis) with the method used here may address these limitations.

3. To provide insight into how heuristics can be characterized and classified so that we may understand how they bring value to the design process.

- Three attributes have been identified that are associated with the value of a heuristic: reliability, frequency of use, evolution. Designers were asked to evaluate their own heuristics based on these three attributes. There are most certainly other attributes that can be identified and studied in the future. Statistically significant correlations between these three identified attributes; a positive correlation was found between frequency of use and reliability, while negative correlations were found between frequency of use and evolution, and reliability and evolution.
- A beginning classification scheme has been developed, using pre-existing frameworks and paradigms to overlay them onto the heuristics that have been extracted. It is expected that as the heuristics repository grows, this classification scheme will grow and change as well.
- Classification by contextual applicability will allow designers to initially evaluate the relevance of each heuristic to their current circumstance, placing an initial value on the heuristics.

While the JPL A-Team is a specific population, we believe the results of this study can have impact beyond the context of this population. The research method used in this work can transfer to extracting heuristics in all phases of design, and is not limited to the field of space mission design. However, a study in a new field must change the example heuristics given in the beginning of the interview. In following up each interview with a survey, we were able to have designers assign value to their heuristics based on rate of evolution, level of reliability, and frequency of use; these characteristics, along with others yet to be defined, can be used to evaluate any heuristic from any designer. The establishment classification scheme, though specific to the field of space mission design, indicates how a classification scheme for any other subfield might be developed or derived from existing paradigms within that subfield. The heuristics extraction method demonstrated in this work provides a new way to discover and confirm heuristics with designers directly.

CHAPTER 4. ANALYSIS OF PROCESS HEURISTICS AND REPOSITORY CONSIDERATIONS (STUDY II)

Study II aims to contribute to the theory of process heuristics and the methodology for obtaining them from designers, employing the contextual application of complex systems design. There are improvements to be made in the methodology such that adequate information is extracted for future validation and application of heuristics. There is new insight into characteristics of process heuristics (heuristics that guide the design process rather than the direct design of the details of an artifact) based on how they are presented by the designers. It will address what information is needed to have a sufficient repository and what changes should be made in the methodology to obtain this new information.

4.1 Participants

The participants in this study are all designers within one specific group at JPL's Innovation Foundry known as the Architecture Team (A-Team), as described in Study I. In total, eight members of the A-Team participated in the study. Two participants had participated in a previous study with the research team, and the remaining members had no prior affiliation with the research team before the workshop. There was no compensation for participation.

4.2 Methodology

Based on the definitions of Gillham and Yin, this study is a case study of complex system design experts at the Jet Propulsion Laboratory using a mixed methods approach of interviews and artifact analysis [60, 63]. This study documents process heuristics through a focus group interview lasting 30 minutes and was part of a larger sequence of studies to develop a repository of heuristics for a group of designers at the Jet Propulsion Laboratory (JPL). The group interview took place within a workshop developed to present the progress on heuristics research at JPL described in Study I, followed by the designers discussing various aspects of their own heuristics and how cataloging this information may be valuable to them. This method gave the researchers the ability to facilitate interaction and discussion with the participants, while ensuring they understood heuristics and had the ability to see heuristics in their own work. The artifact analyzed from this study is an affinity diagram of process heuristics used within the A-Team. The study concludes with a second interview process with two A-Team leaders, conducted post-workshop. Studying this population of mission designers can be considered analogous to other complex systems design teams, although this study could be performed with designers of any group in any domain of engineering.

Before performing this study, institutional IRB approval was received to perform the human subjects study as designed. Then, participants were recruited to the study by email, and those that agreed to participate signed a consent form before the study began. The study took place at JPL in the same room used to conduct A-Team studies, known as Left Field. Left Field is favored for its large whiteboard space, configurability, and comfort. This location gave participants a comfortable, familiar environment during the study. The workshop began with a 30-minute presentation to participants to deepen their understanding of heuristics. This presentation began by defining heuristics and the motivation for studying them. Then, heuristics collected in a prior study with the A-Team were shown, along with a preliminary analysis of those heuristics [14]. At the end of the presentation, the focus group interview began. The participants spent 30 minutes going through the following discussion questions:

• Have our current findings matched your concept of the heuristics you use?
- What are we missing in terms of how we are thinking about the heuristics themselves, characterization, and organization/presentation?
- What would be the most valuable way for you to interact with your own catalog of heuristics?

After 30 minutes, the workshop then turned toward individual brainstorming of heuristics. Participants were instructed to focus specifically on process heuristics that guide the design process, rather than the design choices for details of an artifact. An example given as a process heuristic used in A-Team studies was: "When designing an A-Team Study, split the requirements, problems, and solutions into three different brainstorming processes." Each participant was given ten minutes to write down as many process heuristics as they could think of that are used during A-Team studies, using the sticky-notes provided. The sticky notes method is the A-Team's typical method of brainwriting, so this activity was something each participant was familiar with and comfortable with performing. They were encouraged to write these heuristics in context-action form, although heuristics were not rejected if they could not do this in the allotted time [14]. After the ten minutes elapsed, all members placed their own sticky notes on the floor-to-ceiling whiteboard wall and attempted to categorize the heuristics on the board, similar to how they would in a typical A-Team study. This process is often called Affinity Diagramming in design [48].

Once the data was grouped by the participants, two leaders of the A-Team led the discussion for labeling the large categories along with subcategories. This required some modification to the initial affinity mapping performed by participants. They broke the heuristics into subcategories after the workshop, without the input of the rest of the participants. They did this based on their own understanding of the heuristics listed and

typical A-Team language and processes. Figures 4.1-2 show some of the sticky notes on the whiteboard and the attempt to group the heuristics.



Figure 4.1 – Example Heuristics Placed on Board using Sticky Notes.

After this process, the researchers interviewed both A-Team leaders individually for more insight into the heuristic categories and contexts surrounding the extracted process heuristics. These interviews were in-person at Jet Propulsion Lab and lasted about one hour each. These interviews were not intended to extract additional process heuristics, but to understand more about the environment in which the current set of heuristics were being used. To generate interview questions, researchers collectively studied the heuristics and hypothesized additional information about the A-Team that may be missing. The information gathered from these interviews is discussed throughout the analysis and discussion section for each primary heuristic category. Data was collected during all interviews and the affinity mapping process by recording all audio, then transcribing the recordings afterwards for analysis. Artifacts collected during heuristic generation included the physical sticky notes containing the heuristics. The affinity map containing heuristics and heuristic categories was documented through photos of heuristics on the floor-to-ceiling whiteboard wall in their respective groups.



Figure 4.2 – Example of Categorized Heuristics during Affinity Mapping.

4.3 Results and Analysis

From the eight participants, fifty heuristics were produced from the study over a ten minute brainwriting period. The average number of heuristics per participant was 6.25 heuristics, with the highest individual total being twelve heuristics and the lowest being four heuristics. The number of process heuristics generated per participant is shown in Table 4.1. The full set of heuristics generated is listed in Appendix D. The heuristics are

presented solely as a portion of the study results, and they are not necessarily recommended for use outside of the A-Team at the time of this dissertation's publication.

The categorization performed after affinity mapping led to five main categories: people, tools, resources, pre-study processes and study processes. Study processes is the largest category with 50% of the heuristics, and the other four categories contain the remaining 50%. The breakdown of heuristics by category is shown in Figure 4.3. Appendix D includes the primary and secondary categorizations for all heuristics.

Participant	Number of Heuristics
А	6
В	4
С	4
D	4
Е	12
F	5
G	5
Н	10

Table 4.1 – Number of Heuristics Generated Per Participant.



Figure 4.3 – Percentage of Heuristics per Primary Category (N = 50).

The following subsections are based on the five primary categories uncovered during the study. Each subsection describes the relevance of the category to the A-Team through information extracted during the interviews with A-Team leaders. Then, highlights from the group interview considered relevant for how heuristics impact that specific category are presented. The analysis ends with an assessment of the process heuristics taken from the study and the methodology for extracting them.

4.3.1 A-Team Heuristic Category: People

Figure 4.4 presents an overview of the people typically present in an A-Team study. The A-Team prefers 12-15 participants in each study so that different strengths will overlap and lead to an answer/solution. The people in an A-Team study can be split into 3 main groups: the Client team, the A-Team (study lead, assistant study lead, facilitator, and documentarian), and the Subject Matter Experts.



Figure 4.4 – Typical A-Team Study Setup.

4.3.1.1 Client Team

The client is the person/group internal to JPL who is paying for the study, and the client lead represents the client at all A-Team meetings. Clients approach the A-Team for assistance with a problem, which may require some combination of generating ideas, determining feasibility, and/or exploring trade-spaces for new mission concepts for NASA proposals, science communications, the Program Office's strategic objectives, and/or technology infusion.

4.3.1.2 <u>A-Team</u>

For the A-team, the study lead is responsible for developing all aspects of the study. The assistant study lead will support the study lead prior to, during, and after the study. The assistant study lead notes will be focused on higher-level ideas and conclusion that may not be captured by the documentarian. The documentarian ensures everything in the study is documented in an online report called "the wiki".

The facilitator is responsible for guiding the participants through the study agenda and is necessary for a well-run study. The facilitator knows how much time to spend on each item and ensures the study remains focused on the preset goal and objectives. They should know when to limit someone who is dominating the conversation or taking the team down a "rabbit hole". While the facilitator's role is limited before the study, they are the one person in the room responsible for meeting the study goals. A facilitator must be able to adequately think on their feet, guide conversations, work well with strangers, and feel comfortable discussing ideas that may be outside of their area of expertise.

4.3.1.3 Subject Matter Experts

Subject matter experts (SMEs) fill the remaining spots in the study. The client may suggest specific SMEs they desire, or if a specific individual is not known, will let the A-Team Leadership find individuals with the desired knowledge from the various technical divisions at JPL. If an unusual subject is being discussed, the team may need to find an SME external to JPL, but that is rarely the case. One challenge to selecting subject matter experts is finding people who work well in the A-Team environment. Some SMEs are too socially reserved to be effective in this type of environment. Another challenge is the client's tendency to pick their own SMEs for their study, leading to less objective assessments. An insider may be biased about certain aspects of knowledge, expertise, or diversity of the study team. In either case, success will rely on people being willing to think outside the box and participate, regardless of the subject matter.

The heuristics in Appendix D for this category are related to making sure the right people are put in the room for each A-Team study. In addition to this set of heuristics, the group discussion highlighted awareness of situations in which heuristics could improve their current decision-making process. For example:

Participant D: "An example is, if I'm having a study lead, an assistant study lead, and a facilitator for a study, do I want them to be an expert in the topic we study? In that case, they are bringing their own biases and limitation. Or do I want them ignorant in the field? In this case, they won't know anything about it and [will be] really open. I've never solved that one."

The study lead should do some research to understand the problem before the study, but they are not expected to be an expert in the topic. One issue with choosing the study lead is balancing between one who is an expert on a topic but enters a study with biases, versus one who knows little about the topic at hand but has less bias. Although the A-Team has not noticed any correlation between a study lead's knowledge and the success or failure of that study, they believe chances of success can be improved with better decision-making about who to put in the room during A-Team studies. The topic of unconscious heuristics also appeared during an interaction between two participants:

Participant E: "I think the atmosphere is different. Sometimes you want adversaries in the study for generating ideas, because you don't want to end up with 1000 different concepts. I think that does change contextually."

Participant A: "Do we really think about that consciously? I don't think so. I don't think I say, 'I need to get some competition in here."

What one person considers conscious, another may consider unconscious, whether it be through a larger period of experience, less ability to recall past experiences, or some other reason. Depending on who is interviewed in the A-team, different heuristics will be articulated and collected. These are factors that play into extraction by interaction with the designer, and should be considered when choosing an extraction method.

4.3.2 A-Team Heuristic Category: Pre-Study Processes

When someone initially approaches the A-Team and expresses interest in having a study, their request is recorded in the "Hopper", a database of potential future studies maintained by the A-Team. If the client is ready to move forward with a study, a client meeting between the client and the A-Team is set to move the idea from the Hopper into the planning stages. From there, 1-2 planning meetings will provide adequate preparation for the study.

4.3.2.1 Client Meeting

The A-Team always tries to plan at least one month between the client meeting and the day of the study to ensure adequate time for any background meeting or proper "prework" before the study. For example, the team may want to create a trade space tool for spacecraft design and trajectories before a study on spacecraft configuration. The client meeting does not deliver all the information needed for the study, but rather the basic information needed to start the conversation. Many questions must be answered for a successful study, such as:

- What is the clearly defined goal of the study?
- What are the objectives of the study? (Objectives are considered more quantitative than the study goal)
- What is the final product the client wants at the end of the study?
- What presentations will be necessary to give all participants an understanding of the problem?
- What would the framework of the study look like (i.e., a rudimentary agenda)?
- Who does the client want to participate in the study?
- What SMEs are required to successfully reach the study goal objectively?

4.3.2.2 Planning Meeting

An additional meeting called the "planning meeting" will check on the progress of recruiting participants and making sure there are enough people to have a successful A-Team study. The planning meeting is 2 weeks before the day of the A-Team study, and a second meeting one week before the A-Team study may be necessary if new information is obtained or other details have changed. The reasoning behind the length of time set aside to plan an A-Team study is more about getting a time that works for the desired participants. The farther out it is planned, the easier it is to get on everyone's calendar.

The heuristics in Appendix D for pre-study would most likely be implemented during the same time frame as the client and planning meetings. During the group discussion, participants seemed most encouraged about a repository of their heuristics for this planning stage of the study, because that is where reliance on other A-Team members is at a minimum. As shown in the quote below, new study leads could benefit from obtaining the heuristics of more experienced members of the team.

Participant B: "When we are in the…planning phase, we are not doing an A-team study, we don't have everyone in the room, you are basically on your own planning stuff. In that case, if you have one repository of heuristics useful for the A-Team, it's probably this one. How to do an A-Team study – how to set one up – how to run it. Because we are not too good at maintaining our A-Team institutional knowledge. You know, what do you do when you're planning a study?"

4.3.3 A-Team Heuristic Category: Study Processes

A-Team studies focus on three main levels of concept maturity: idea generation, feasibility assessment, and trade space exploration, as shown in Figure 4.5. The study processes will follow the agenda created by the study lead, through collaboration with the facilitator and the client. The heuristics in Appendix D for study processes mostly include guidelines that the facilitator may employ during the study. Due to a lack of standard training of facilitators outside of experience running studies, a repository of heuristics for facilitators would benefit the onboarding of new members of the A-team, especially in the facilitator role.

During the interview, several participants highlighted a willingness to evolve current methods or adopt heuristics from outside sources. The example quote below portrays a study in which the idea generation phase was modified in hopes of identifying a better set of design concepts. Documenting the success of new and previous heuristics may improve the selection of processes for future studies.



Figure 4.5 – An Example A-Team Study Timeline.

Participant D: "An example of how it (the heuristic) evolves. We used to write your idea down on a sticky note... Somebody stands up, reads their sticky notes and puts them on the board. Then we organize it. We usually do it, we still do it. But then, one time we did a study where we instead had people stand at the board and write on their sticky notes while we were up there. We got a different outcome. The benefit was we didn't get as many repetitions because we could see things and build off each other more quickly. The other side is people were way more biased, so there is an upside / downside. I actually think I prefer the second one where we all stand at the board."

4.3.4 A-Team Heuristic Category: Tools + Resources

4.3.4.1 Software Tools

Figure 4.6 lists the tools and resources commonly used by the A-Team. The software tools category is specifically for more software-oriented tools that assist the A-Team during a study. For example, the Hopper wiki, described earlier, is a tool that organizes potential future studies. The wiki is divided up into A-Team Core and A-Team Studies. A-Team Studies are divided into Client Notes, Hopper, Planning, In Session, and Completed. The contents of the In-Session wiki is passed on as a final product to the client,

as well as stored by the A-Team as a reference for future studies. All study participants have access to the wiki after the study. Once the study is complete, the wiki is cleaned up, and the study lead ensures everything the client requested is contained in the wiki. This is the usual final product delivered to the client and documents the study for future usage. Figures 4.7-8 show example wiki page outlines shared with participants.



Figure 4.6 – Overview of A-Team Tools and Resources.



Figure 4.7 – Example Outline of Wiki Content.



Figure 4.8 – Example Outline of Wiki Content.

4.3.4.2 Physical Resources

An introduction package distributed at the beginning of a study contains the study goals and objectives from the client meeting notes, a list of desired participants, and an overview of who the A-Team is and what they do. This keeps members on the same page for the study without having to restate basic information throughout the meeting. It also helps participants who are new to the A-Team understand the full potential of the A-Team; people will often only know about one specific thing the A-Team does and not the full range of study types and tools. Information from client notes and the intro package are placed in the wiki, along with everything documented during the study.

4.3.4.3 Design Methods

Additional resources include the different design methods implemented throughout a study. Storytelling methods are used during studies that describe the desired science of a particular mission. Quad charts help participants understand a concept's strengths, weaknesses, and how the concept can be moved forward. Brainwriting is used for individual idea generation on sticky notes, followed by multi-voting to identify the strongest ideas. Most A-Team studies are skewed toward the idea generation type because it is hard to complete a full tradespace exploration during the time available; a typical A-Team study is conducted in half-day segments over a span of 1-2 days. However, JPL is currently working to develop more and more tools to support high-level and quick tradespace exploration.

4.3.5 Heuristic Repository

Appendix D contains heuristics for consideration and implementation of tools and resources. During the group discussion, participants reflected on a heuristic repository as an additional tool for the A-Team and how that may impact future studies. There were many concerns towards a heuristic repository discussed during the workshop. These items were not necessarily opposed to a repository, but rather factors that should be acknowledged when determining a plan of action for extraction. The first factor is the vision for implementing this type of repository. It is important to know the population one is designing for, so that the most efficient categorization can be determined. For example, the quote below suggests that the A-Team may prefer risk related descriptions, whereas another team may find this less useful. Additionally, the A-Team will be concerned with heuristics originating from many different backgrounds. In this case, it would be necessary to consider efficiency based on the breadth of the repository. Would it be best to combine all heuristics from all backgrounds into one repository? How many heuristics become too many to navigate? How are misuse and unnecessary search efforts prevented?

Participant F: "We are in the space industry, and we worry about risk maybe more than other technical fields, because you can't fix things in space. Do they map into all those categories, or would they be a separate category?"

A second concern highlighted by the largest number of participants was the ability to sense when a heuristic is not useful relative to the context of the study. A bad heuristic may take the group down a "rabbit hole", but how do you know which heuristics are not useful for a particular study?

Participant G: "I think we are getting to why this conversation is important for the A-Team specifically. Because we bring a lot of experts in, but all of us who are planning, executing, facilitating studies need to be aware of these things, and awareness that people's heuristics can be helpful but also hurtful. We need to walk the line to determine those types of things."

The first two concerns lead directly into the third factor - how much information should be included in an articulation of a heuristic? The amount of information will correlate with the detail with which the heuristics are extracted. The level of granularity and supplemental information will affect the categorization, as well as the ability to determine its relevance to the design problem [5]. Ultimately, a designer should have enough information to determine whether the heuristic should be used in the current design context.

Participant F: "When you have these heuristics, you capture it somehow. But you capture it to a 100-character tweet? Do you have a whole wiki on the topic? Do you have cross-links to other items?"

One final concern is how to maintain a repository of heuristics once it is created. This may depend on how often the heuristics require updating and how often new heuristics are developed. The resulting tool must address how much of a burden will be placed on designers for updates, as well as who would oversee these updates within a group setting.

Participant B: "There are three elements here. The first part is capturing them. The second is disseminating them. Have you thought about how to maintain them? How many resources are required to keep up with them and the effort every time new information is obtained? It is a lot of work."

4.3.6 A-Team Process Heuristics

In this study, participants could construct most heuristics (68%) into context-action form, while the other 32% did not include a context. Of those 32%, about half of the heuristics wrote out the actions to be taken, and the other half simply listed the title of a process without explanation. The lack of context may possibly be due to the time limitations or the inability to simplify the context for the action. These heuristics were further analyzed as a step towards addressing some of the previously listed concerns about developing a heuristic repository.

The heuristics captured tend to require application externally to the entire A-team, instead of an individual's inner mental processes. An example of an inner process is "When

facilitating, use the de Bono Methods". The de Bono method is something the facilitator consciously keeps in mind during the study, but it is not something explicitly followed by the rest of the study team [101]. On the other hand, the heuristic "For trade studies, use science value metrics to differentiate and compare mission architectures" would be carried out explicitly by the entire team. The heuristics also tend to apply to either the facilitator or the study lead, when compared to other members such as the client lead, documentarian, or subject matter experts. These characteristics have an impact on the repository when considering its targeted user. The study lead may struggle with navigating a repository with too many heuristics that are not applicable to their role on the team. On the other hand, the study lead may have a more accurate mental model of the study to be performed if they are fully aware of the heuristics each facilitator brings to the study. This awareness of other heuristics in the design space may bring its own impact to the decision-making process.

The heuristics captured appear to be mostly informal processes, rather than formal design methods commonly found in literature. For example, a formal process heuristic for idea generation would be "brainstorming", and an informal method would be "If you have less than 7 people in a study, add SMEs." Processes were considered formal if the heuristic was listed as a named or titled process, such as the "de Bono" methods or the "double diamond" design process [102]. Of the six heuristics labeled as formal processes, five of them were categorized as in-study processes. It is hypothesized that the formal process heuristics originated through sources outside of an A-Team study, whereas informal methods were more likely to be developed and refined through experiences within the A-Team studies. This would imply that the designers are relying mostly on experience alone for planning studies and getting the right people, tools and resources in the room. From a value perspective, it is possible that the designer may place higher value on heuristics developed from their own experiences compared to those from outside sources, or that the

designers may not be aware of external heuristics that could potentially add value to the process. These hypotheses will be tested in future studies that document how the heuristics originated and more accurately assess the value designers place on heuristics.

The way the heuristics were framed by the participants was analyzed in a variety of ways. Heuristics were overwhelmingly presented as positive "do" actions rather than negative "do not" actions. An example positively framed heuristic is, "for concept generation, have X (person) in the room to generate crazy ideas that get people thinking." A similar heuristic in the negative frame is, "for idea generation, do not judge ideas." Both heuristics aim to generate as many ideas as possible. The positive frame includes a "disrupter" who can get others to think outside the box. The negative frame hopes that a lack of judgement will encourage participants to speak out and present ideas freely without fearing negative feedback.

The process heuristics were also mostly contained to one step each, rather than multiple steps in the process. Only 18% of presented process heuristics included more than one step in the process, and no participant presented more than 3 steps in a single heuristic. For example, the heuristic "When the A-Team gets larger than 15 people, break up the study into smaller groups" has only one step. A multi-step heuristic would be "For brainstorming, the group stands at the board, writes ideas on sticky notes, and places them on the board." This may be due to the lack of time or ability to simplify each step of the process, or it may be that the participants viewed their heuristics as a single step in time, rather than a series of steps.

There were also situations in which designers delivered the same action, but had different perspectives on the context. For example, two participants presented heuristics to move conversations to the "parking lot", an A-Team method for documenting and leaving conversations for later that are not beneficial to the progress of the study. One participant values this action when topics become too specific, while the other values this action when a member becomes too outspoken on an issue. The actions are the same, but the participants have different perspectives on the context in which the action is valuable.

In a similar example, two heuristics had related actions that differed in being framed as proactive decisions versus reactive decisions. The proactive heuristic, "for timeline planning, keep the group small", is preventing an undesirable situation, a group of participants too big for optimal functionality. The reactive heuristic, "When an A-Team study gets larger than 15 people, break up the study into smaller groups", is a process implemented in reaction to finding yourself in that undesirable situation. For each heuristic, the goal is to keep the A-team at an effective size, but the two participants viewed the situation from different perspectives. The proactive heuristic appears to be applicable to a larger set of studies that will involve planning, but the reactive heuristic may apply only to a smaller sample of studies that go over the typical A-team size. Most heuristics were presented in the proactive form.

In a repository of heuristics, the characteristics presented above may all have a direct impact on how the designer mentally assigns a value to the heuristic. Future work should focus on the amount and types of information presented with each heuristic, and the different criteria that a designer may use to analyze a heuristic, in order to understand how their documentation can provide the best value assessment possible.

Overall, the heuristics generated by participants are hypothesized to be highly transferable to domains outside of space mission design. Only three heuristics total were specific to mission design, and only two heuristics used language specific to the A-team. None of the captured heuristics were directed towards a specific artifact. When viewing heuristics in terms of value, a heuristic may be considered more valuable if it can be implemented by the designer in a variety of contexts. However, the heuristics have not yet been tested in separate studies, so future work will be required before any heuristics presented are recommended for use outside of the A-Team.

4.3.7 Analysis of Methodological Outcomes

One benefit of the method used in this study was ensuring a proper comfort level for the participants. The location of the study, the collection of participants, and the agenda of the study (presentation, discussion, brainwriting) made it similar to previous A-Team studies, which may have made them more willing to speak and be engaged. Providing examples of heuristics used within their team from a previous study may have helped improve understanding of heuristics, or at least have helped participants see where the heuristics are applicable in their own work. The presentation and discussion before the heuristics generation helped designers see the need for understanding their own heuristics and may have motivated them during the generation phase.

This study allowed the A-Team members to group the heuristics on their own, as opposed to having an outsider group them. This may help the A-Team implement the heuristic repository into their current processes, but it does not necessarily mean this is the best way to categorize the heuristics. Therefore, this could also be a limitation. This same idea applies to the verification of the heuristics. It is beneficial that the heuristics have been self-validated, but a more robust validation will confirm these heuristics through triangulation using additional methods such as observations or additional artifact analysis from within A-Team studies. Further limitations may include biased results based on the heuristics that the research team showed them during the presentation, causing an effect such as design fixation [103]. Additionally, the mixture of various experience and leadership levels in the study may have created pressure / influence during heuristic generation. Some participants may have felt uncomfortable articulating a heuristic that may have surprised higher management or be refuted by other participants. However, the A-Team does its best to limit that type of hierarchical culture, because all studies tend to have a diverse set of people in the room.

It is hard to say when the list of heuristics is saturated or has become robust. There is no limit on the number of heuristics that may be used, and it would take many additional studies to ensure the list is exhaustive. Future work may include an additional round of heuristic generation to fill in the gaps based on the categories.

4.4 Conclusion

This study presents a unique case study using interviews and artifact analysis surrounding a two-hour workshop with the A-Team at the Jet Propulsion Laboratory. The interviews gave insight into the role of heuristics within a complex systems design team and how documenting them can be valuable. Within the A-Team specifically, there is a need for documenting the process heuristics for planning and facilitating an A-Team study. This case study resulted in an initial extraction of process heuristics currently used to handle these aspects of a study.

The heuristics generated also allowed for an overview of how mission designers at JPL perceived their own process heuristics. It was found that most heuristics were comprised of a single, positively framed step to be carried out within the team, not just by an individual. Participants were also able to produce mainly informal actions they take rather than formalized textbook approaches to design. The process heuristics captured are hypothesized to be generic enough to be transferred out of the mission design domain and into another, if desired. Future work will include building a repository of these heuristics to recommend how and when they should be used. This will begin with reaffirming the heuristics extracted are valid within the A-Team. A supplemental ethnography or case study of observations, artifact analysis, etc., must be created as a triangulation process for validating heuristics. From there, maturing the repository will include creating a process to understand when the heuristic adds value to the design at hand, and determining how to maintain the relevancy of the repository over time.

CHAPTER 5. ASSESSMENT OF HEURISTICS AS AN ERROR MANAGEMENT BIAS (STUDY III)

5.1 Introduction

Study III characterized heuristics from the broader scope of cognitive bias and adapted rationality. This starts with an extraction of biases in design teams. After identifying bias in each design team, the study sought to differentiate and discuss those biases considered heuristics with the intent of error management.

5.2 Participants

The 36 participants of this study were all students in a graduate level engineering design course. The class consisted of 40 students broken into ten design teams, four students per team. Only one team in the course did not fully consent to participant in this study, and they were excluded from all results and analysis. Participants consented to giving the researchers access to all individual and team course deliverables.

This course met twice a week, 75 minutes per meeting, in the Spring 2020 semester of the institution. The team project was 50% towards each participant's grades for the course, and extra credit was provided to participants who allowed their project work to be included in this research study. This was a 16 week course, where the first project assignment was due in week six and continued for the remaining ten weeks. During week ten of the semester, it was announced that classes would be moved online for the remainder of the semester. This announcement came after customer needs had been obtained by the students, but before concept ideation and selection was submitted. This means that the selection, feedback and iteration processes were submitted after courses were made fully remote. The syllabus for the course had five main outcome, summarized below:

- Describe design methods, tools, and terminology.
- Analyze and evaluate when and why particular design methods are or are not appropriate.
- Apply multiple design methods and tools in individual and team settings.
- Participate in team design activities.
- Communicate design process choices and outcomes in written and oral formats.

A demographic survey showed that the participants consisted of 23 men and 13 women. The majority also classified themselves as White (20) or Asian (13). 35 of the 36 participants were between the ages of 21 and 26, with one being older than 27. There were eight participants in a PhD program, 23 in a Master's program, and five senior-level undergraduate students. There were 30 participants in mechanical engineering, with eight participants adding additional disciplines, such as robotics, computer science, aerospace, biology, and chemistry related fields. The remaining six participants were from aerospace, chemical, or electrical engineering programs and not enrolled as mechanical engineering students.

5.3 Methods

The approach to the methodology for this study was to gather as much data within the designers' natural working environment as possible. This was done by combining data from real project deliverables with reflection surveys that were integrated into the course. There were five main surveys given to students. The surveys were distributed after teams completed five critical outcomes across the semester: project selection, customer needs and target specifications, concept selection, design refinement, and the final design report. The course deliverables accessed by the researchers associated with each critical outcome can be found in Table 5.1. The final design report contained an economic analysis, which was not a standalone course deliverable before the final report.

Survey	Corresponding Course Deliverables Accessed
Survey 1	Individual Project Topic Ideation
	Team Project Proposal
Survey 2	Customer Needs Identified with Ranking
	Target Specifications
Survey 3	Individual Concept Ideation
	Group Concept Ideation
	Concept Selection and Selection Process
Survey 4	Design Concept Feedback
	Design Iteration
Survey 5	Final Team Project Report

 Table 5.1 – Course Deliverables Relative to the Surveys Distributed to Students.

The surveys were a mix of Likert scale response questions, multiple choice, and openended text-entry questions. The full survey set can be found in Appendix E. There were similar questions that occurred across all five surveys, briefly listed below. The purpose of these questions was to have some consistency across the project for comparison across phases.

- Role in decision making: Participants provided Likert scale responses to how they felt about the decision making process during the design phase/tasks. This includes whether they advocated for their ideas/beliefs, felt satisfied with decisions made, felt heard when voicing opinions, and felt invested in the decision making process.
- Effort: Participants documented the amount of effort (in hours) for the most recent design task. They selected from a list the amount of hours of individual work, as well as hours spent working as a team.
- **Perception of the market:** Participants provided Likert scale responses to how they felt about the market after major design tasks were completed. This includes the size of the market, if they felt included in the market, the level of innovation in their design idea, and if they planned to continue the project after class.
- **Design methods and personal duties:** Participants chose from a list or wrote-in the methods used to achieve their design tasks, as well as any duties they were assigned individually during that time.

Aside from common survey questions, there were other questions tailored specifically to the most recent course deliverables for the project. These unique survey questions are described below, and their contributions towards identifying biases will be discussed in the results section for each corresponding bias.

5.3.1 Survey 1

In addition to the similar survey questions listed above, participants were asked to list what they believed to be their top three ideas for the individual project topic ideation assignment, in ranked order from best idea to third best idea. For each idea they developed, participants provided information such as the amount of research performed and how they were able to develop the idea (personal experience, identifying current solutions, etc). Then, out of the three ideas, participants were asked which idea they would prefer if considering specific factors, such as sustainability, personal day-to-day relevance, novelty, or profitability.

Survey 1 also presented questions that had participants prepare initial predictions for which five customer needs would be relevant before the customer needs assessment. Similar text entry questions were asked for a description of their first idea of what the solution would look like, as well as if they were aware of any current solutions on the market.

5.3.2 Survey 2

Survey 2 included unique questions concerning how many stakeholders were interacted with individually and as a team. Likert scale statements asked how students felt about the stakeholders and how the customer needs assessment impacted their view of the project. Similar to Survey 1, participants ranked the three customer needs they believed to be most important to the project. For each of the top three needs, Likert scale statements asked participants questions, such as whether they were the person who identified this customer need, if they felt the need would be easy to ideate for, and whether they had the time and resources to meet the customer need. A similar ranking and description process was performed for their personally ranked top three target specifications. Survey 2 ended with another prompt asking participants to describe what they believe the solution will look like after delivering the customer needs and target specifications.

5.3.3 Survey 3

For Survey 3, participants were asked how they felt about the individual and team ideas generated. This included statements such as how involved the team was in the process, the quality of ideas, and the difficulty they encountered in generating ideas.

Similar to Survey 1, students were asked to write out what they believed to be the best three ideas of all the ideas generated, in ranked order from best idea to third best idea. They were asked various aspects for each idea, such as if they contributed to the idea, whether it matched their vision of the solution from the beginning of the semester, and how other team members felt about the idea. They were asked to choose their preferred idea based on the same factors presented to them in Survey 1. They were also asked for their opinion on the final concept with which the team chose to move forward.

Survey 3 ended with Likert scale statements asking participants how they felt about moving into user the feedback phase, followed by an open-ended description of any assumptions of shortcuts students believed their teams would need to take to receive virtual feedback. These questions were implemented specifically due to the semester being moved to fully on-line courses before the user feedback process due to the pandemic.

5.3.4 Survey 4

Survey 4 asks participants for their thoughts about the end users chosen for gathering user feedback, including whether they were the most available people or the best depiction of their market. They also provided opinions on the process used to gather feedback, such as the method for communicating the design and the severity of refinements needed based on feedback. Lastly, participants listed what they believe to be the three most important design decisions made, ranked most important to third most important. These should be specific decisions concerning whether to modify or not modify aspects of the design, and how the design was modified, based on the user feedback received. For each decision, they provided Likert scale agreement with statements such as if they agreed with the decisions, if it included design refinements, if they recommended the decisions, and if they were justifiable decisions.

5.3.5 Survey 5

Survey 5 asks participants to describe how they felt about the economic analysis performed by the team, as well as the final design. They were also asked a series of statements regarding what they would have done differently, such as being more vocal or spending more time on ideation. These statements were paired with Likert scale responses. Then, participants were asked to describe one major decision about the design or design process that they would change if they could do the project over again, and if they were influential in making this decision. Similar prompts asked participants to describe one major decision that they believe was critical to the design success, as well as any issues they encountered and if they should have seen these issues coming beforehand. Survey 5 ends with demographic questions. In addition to basic demographic questions, participants were asked to respond to a set of statements, listed below, as honestly as possible.

- I am comfortable sketching my ideas.
- I am a creative person.
- If I have spent more time on an idea or project, I am more reluctant to abandon it.
- If I am the owner of an idea, I am more inclined to want to pursue that idea on a design team.
- If I have a hypothesis, I hope it will be confirmed by the data I collect.
- Usually, the solution that exists to a design problem (the status quo) is a good one.
- When I write interview or survey questions for user feedback, I am careful to consider positive or negative wording.
- When I'm tired or stressed, I think I make different design decisions than I would make otherwise.

These questions supplement additional CATME demographic questions that were asked by the instructor at the beginning of the semester. Besides basic information such as age, sex, race, discipline and year in their degree program, the following additional information was collected at the beginning of the semester:

- "Big Picture" Participants labeled themselves as a visionary, preferring ideas, preferring detail, or a more balanced approach to seeing the big picture.
- "Leadership Role" Participants labeled themselves as being a follower, preferring to follow, preferring to lead, or a more balanced approach.
- "Leadership Preferences" Participants labeled themselves as preferring a single leader, shared leadership, or one leader with input when defining the leadership in a team setting.
- "Experience" Participants labeled their level of comfort with being hands-on, ranging from no experience to expert level.

5.4 Results

5.4.1 Bandwagon Effect

To identify the possibility of the bandwagon effect within design teams, we identified if participants "advocated" for their ideas and beliefs and paired this with their satisfaction with group decision making and the design problem moving forward. The results are focused on participants who did not advocate for their beliefs, but continued with the project as the team believed necessary. This provides the appearance that they are simply following along with the popular opinion of team decisions. Questions regarding advocating and satisfaction were implemented in all five surveys across the semester. Responses to Likert scale survey questions were are shown in Figures 5.1-2 below.



Figure 5.1 – Participant agreement towards advocating for their own beliefs across design phases.



Figure 5.2 – Student responses, across all teams, to being satisfied with decision making across design phases.

From Figures 5.1-2, it's clear that the majority of students state that they advocated for their beliefs and were satisfied with the team's results. We looked closer for those who

did not agree that they advocated during decision making with their team, but agreed that they were satisfied with the outcomes. For this analysis, we included participants who answered "disagree" or "neutral" as those who did not agree. For example, eleven participants (31%) listed "disagree" or "neutral" for whether they advocated for their own project topic ideas. However, all eleven participants stated they were satisfied with the final topic chosen. This is shown for additional project deliverables in Figure 5.3.



Satisfaction without Advocating for Beliefs

Figure 5.3 – Participants that felt satisfied at each stage without advocating for their own beliefs.

The stages in Figure 5.3 are in chronological order for class deliverables, from project selection to the economic analysis. The number of participants that fall under suspicion for the bandwagon effect decreases as the semester progresses to concept ideation and selection, then increases again as the semester ends. This could be due to project or semester fatigue, or it could also provide us with how much students value each portion of portion of the process. For example, participants may value the ideation and

selection process the highest, and they are willing/susceptible to fall into the bandwagon effect at other times. Across the entire semester, there were 48 total survey responses listed as "neutral" or "disagree" for advocating for their ideas or beliefs. Only 7 of these (15%) did not report being satisfied with decision making. This means the majority of team members who are not speaking up, are also not reporting any evidence of displeasure.

Demographic data from the beginning of the semester was used to look for other explanations in the results. One significant finding was produced: the participant's leadership role preference was significantly correlated with the average satisfaction produced. For this significance, an independent samples Kruskal-Wallis test was performed to compare non-parametric data across more than two groups. Then a pairwise comparison was performed to account for comparisons across each group. There were three groups for this analysis based on participant responses to the CATME survey: those who prefer following, those who prefer a balanced approach, and those who prefer leading in teams. There was one participant in a fourth group (follower), but this category had only one participant and therefore could not be used for comparisons. For the satisfaction survey questions shown in Figure 2, an average satisfaction was produced for each participant. The results showed that participants who prefer leading were significantly less satisfied on average than participants who prefer a balanced approach between leading and following (H(2) = 7.057, P = .029). This may show us that students who take a more balanced approach are more likely to fall in line with the majority opinion, and lean on their leadership skills when there is no consensus. However, this speculation would require more in-depth assessment than the data can provide and could be left to future work.

One additional finding from the demographic CATME data may show that other biases intersect the ability to avoid the bandwagon effect. Participants were asked: "If I am the owner of an idea, I am more inclined to want to pursue that idea on a design team." As participants felt that they are more inclined to pursue their own ideas on a design team, they were statistically significantly more likely to advocate for their own beliefs during the concept selection process (Spearman's $\rho = 0.368$, p = 0.029, n = 35). This shows that it is possible that those who have some awareness that they prefer their own ideas, may have been less susceptible to fall into the bandwagon concept.

Additionally, this data from Figure 5.3 is broken down by teams in Table 5.2. The results show that Team 7 consistently was above the team average when it came to number of participants who may have shown symptoms of a bandwagon effect. Reflections in the final survey may indicate this type of bandwagon behavior as well. When asked what decisions they would redo if they could do the project over again, one teammate specifically mentioned advocating as the main issue they would have changed. For example:

Teammate 7.1: "Our team made the decision to simply have the seat fold against a wall for simplicity. I did not try to impact the decision made for simplicity's sake, but I believe my team would have listened if I had tried to impact the decision. In hindsight, I might have advocated more for an adjustable seat angle."
	Problem	Customer	Target	Concept	Concept	Econ
	Selection	Needs	Specs	Selected	Refinements	Analysis
Team 1	0	0	0	1	0	1
Team 2	0	0	2	0	1	0
Team 3	0	0	0	0	2	1
Team 5	2	0	0	0	0	0
Team 6	1	1	1	0	0	3
Team 7	3	3	1	1	1	4
Team 8	1	1	0	0	0	0
Team 9	2	1	0	0	0	2
Team 10	2	0	0	0	0	2
Totals	11	6	4	2	4	13
Team	1.22	0.67	0.44	0.22	0.44	1.44
Average						

Table 5.2 – Number of participants by team who did not advocate for beliefs, but were satisfied with decision making.

5.4.1.1 <u>Summary</u>

In summary, the bandwagon effect analysis shows an assessment of participants who did not advocate for their ideas or beliefs but still felt satisfied with the end product. This was presented at the team level as well. From the bandwagon perspective, the satisfaction without advocating could mean that they jumped on board the majority opinion of the team. However, it could also point to the good subject effect, where participants did not want to express a lack of satisfaction and appear as a student causing dysfunction within the team [104].

In reference to previous bandwagon literature, some future adjustments may need to put in place to solidify the bandwagon effects. For example, Barnfield suggests that the strongest bandwagon effects require a change in individuals based on the popular opinion [34]. Additionally, bandwagon effects often need vocal voices so that this popular opinion is heard and seen as the majority opinion [35]. As shown in the reflection from participant 7.1, students may have intuition on whether or not their voice will influence decisions or not. Future surveys may need to direct attention to not just whether someone has advocated, but to ask individuals which opinions were most vocalized, if their own view of this opinion was modified, and if this opinion became a part of the final decision.

5.4.2 Effort Bias

The basis for identifying effort bias was whether the amount of effort (hours) put into a portion of the project correlated with decisions or opinions regarding the design. For each design task, students reported effort in terms of the number of hours devoted to that task. This was done choosing from a pre-determined set of time ranges listed in each survey. For many tasks, they were also asked if they felt that they were "heavily invested" in the process. This was not asked for problem selection and idea generation, because each student was required to provide a minimum number of ideas for each task. Correlations are summarized in Table 5.3-5 below, followed by a written description of results, then a summary of observations. Only significant correlations were included; all non-significant correlations were excluded. These tables separate results into correlations with individual effort (hours), team effort (hours), and feeling that they were "heavily invested" in the process.

Table 5.3 – Spearman's correlations based on individual effort (hours) at each design phase.

Phase	Correlating Statement	Coeff.	Sig.	N
Problem	I was or would have been disappointed if my	0.361	0.033	36
Selection	topic was not chosen.			
	If I am the owner of an idea, I am more inclined	0.356	0.039	34
	to want to pursue that idea on a design team.			
	Usually, the solution that exists to a design	-0.373	0.030	34
	problem (the status quo) is a good one.			
Target	There is a wide variety of end users /	0.385	0.02	36
Specifications	stakeholders.			
	The final design would be a disruptive	0.359	0.032	36
	innovation if introduced to the market.			
	Once this class is over, I plan to pursue	0.423	0.01	36
	development of the final design and market			
	launch.			
Concept	How much effort did you expend individually	0.365	0.028	36
Ideation	on concept selection?			
	I would have preferred our concept to be more	0.437	0.008	36
	technically feasible.			
	I am comfortable sketching my ideas.	0.491	0.003	35
	I am a creative person.	0.527	0.001	35
User	Once this class is over, I plan to pursue	0.425	0.011	35
Feedback	development of the final design and market			
	launch.			
Economic	Once this class is over, I plan to pursue	0.457	0.005	36
Analysis	development of the final design and market			
	launch.			

Table 5.4 – Spearman's correlations based on team effort (hours) at each design phase.

Phase	Correlating Statement	Coeff.	Sig.	Ν
Concept	I feel satisfied by the quality of ideas presented by	0.335	0.046	36
Ideation	other members of the team.			
	Overall, I am satisfied with the concept the team	0.413	0.012	36
	chose to move forward.			

Table 5.4 Continued

Concept	Developing the concept will be difficult and	0.345	0.039	36
Selection	complicated but worthwhile.			
Economic	There is a large market for this product.	0.455	0.005	36
Analysis				

Table 5.5 – Spearman's correlations based on feeling "heavily invested" at each design phase.

Phase	Correlating Statement	Coeff.	Sig.	N
Concept Selection	I feel satisfied with the logical reasoning presented by teammates for choosing the final concept to move forward.	0.458	0.005	36
	I feel satisfied with the criteria used to choose the final concept to move forward.	0.394	0.017	36
	If I am the owner of an idea, I am more inclined to want to pursue that idea on a design team.	0.380	0.024	35
User Feedback	The decision (most important) focused on aspects of the design concept(s) that I was heavily involved in during earlier stages of the project.	0.475	0.004	35
	They were the most available set of people (end users).	0.571	0	35
Concept Refinements	I feel satisfied with the refinements made to the design concept(s), incorporating the user feedback.	0.664	0	35
	I feel satisfied with the logical reasoning for the design concept refinements presented by teammates.	0.484	0.003	35
	The decision (most important) focused on aspects of the design concept(s) that I was heavily involved in during earlier stages of the project.	0.364	0.032	35
	They were the most available set of people (end users).	0.442	0.008	35
Economic Analysis	I advocated for my own beliefs concerning the criteria for the economic analysis.	0.4	0.016	36
	The analysis confirmed my beliefs about the strength of the final design to be profitable.	0.349	0.037	36

5.4.2.1 Problem Selection

There is a significant positive correlation between effort (hours) generating ideas and being disappointed if your own idea was not selected. In reference to CATME and demographic/self-reflection survey data, participants who labeled themselves as "more inclined to pursue their own ideas" expended significantly more effort (hours) generating ideas for topic/problem selection (Spearman's). More effort was also given during this time by participants who disagree that "the solution that exists to a design problem (the status quo) is a good one."

5.4.2.2 Customer Needs and Target Specifications

There was no significance between effort, team effort, or being "heavily invested" and satisfaction with the customer needs assessment. There was similarly no correlation with market perception needs that suggests effort bias. There was no significant correlation between being heavily invested in generating target specifications and market perception or being satisfied with the target specifications generated. There was no correlation found between effort in generating target specifications and being satisfied with the target specifications and being satisfied with the target specifications. However, there were multiple significant correlations between effort in generating target specification. An increase in individual effort correlated with an increase in believing there is a wide variety of end users / stakeholders for this product ($\rho = .385$, p = .02, n = 36), believing this product would be a disruptive innovation if introduced to the market ($\rho = .359$, p = .032, n = 36), and planning to pursue development of this product and market launch beyond the class ($\rho = .423$, p = .01, n = 36).

5.4.2.3 Idea Generation Effort

There was no correlation between effort generating ideas individually and the opinion of one's own ideas or the ideas of others. There was a correlation between more effort generating ideas individually and more effort expended on concept selection ($\rho = .365$, p = .028, n = 36), as well as more agreement wishing the final concept was more technically feasible ($\rho = .437$, p = .008, n = 36). Those with more team effort in ideating were more satisfied with the ideas presented by other members of the team ($\rho = .335$, p = .046, n = 36) and the concept selected to move forward ($\rho = .413$, p = .012, n = 36).

5.4.2.4 Concept Selection Effort

There was no significant Spearman's correlation between effort and market perception or being satisfied with the final concept / concept selection process. There was a significant correlation between team effort in concept selection and the belief that developing the concept will be difficult and complicated but worthwhile ($\rho = .345$, p = .039, n = 36). There were significant correlations between being heavily invested in the concept selection process and being satisfied with the logical reasoning for the concept selected ($\rho = .458$, p = .005, n = 36) and with the criteria used for concept selection ($\rho = .394$, p = .017, n = 36).

5.4.2.5 User Feedback and Concept Refinement Effort

There was no significant Spearman's correlation between effort (time) in feedback/refinements and being satisfied in concept refinements. Those invested in the user

feedback process (time) were more likely to pursue development outside of class ($\rho = .425$, p = .011, n = 35). Being heavily invested in the concept refinement process had a positive correlation with being satisfied with the refinements ($\rho = .664$, p = .000, n = 35) and reasoning for those refinements ($\rho = .484$, p = .003, n = 35).

If participants felt they were more involved in the user feedback process, they also believed the most important decision was based on aspects of the design concept that they were heavily involved in during earlier project stages. ($\rho = .475$, p = .004, n = 35). They held a similar belief about the most important decision if they felt heavily invested in the concept refinements ($\rho = .364$, p = .032, n = 35). If participants felt more invested in the user feedback process, then they believed the stakeholders used were the most available set of people ($\rho = .571$, p = .000, n = 35). This was true once again for those who felt heavily involved in concept refinements ($\rho = .442$, p = .008, n = 35).

5.4.2.6 Economic Analysis Effort

There was no significant Spearman's correlation between being satisfied in the economic analysis and effort (time) or being heavily invested in the economic analysis. Only one correlation was found relative to market perception. Those who put in more effort (time) believed they were more likely to pursue development outside of class ($\rho = .457$, p = .005, n = 36). There was also one correlation for team effort on economic analysis and believing there was a large market ($\rho = .455$, p = .005, n = 36). The more "heavily invested" that participant felt, they were more likely to have advocated their preference on the economic criteria ($\rho = .400$, p = .016, n = 36), and they were also more likely to feel that

the economic analysis confirmed their beliefs about the strength of the design to be profitable ($\rho = .349$, p = .037, n = 36). Those who put in more individual effort were more likely to agree that they felt heavily invested in the economic analysis ($\rho = .637$, p = .000, n = 36).

5.4.2.7 Summary

The correlations for effort show that participants who are putting the most hours in individual effort into the project are also the ones who would hope to continue the project afterwards. This was found in three of the five surveys. These participants are possibly putting more value on the product, based on the amount of effort they have invested. At the team level, more team effort seems to show students are more satisfied with what the team produced as a concept to move forward. They were also more likely to feel that the process would be more worthwhile. Either the amount of effort is producing a high quality design, or participants are placing more value on the outcomes based on how much effort they see the team putting in as a group.

The biggest observation for "heavily invested" participants was that those who felt more invested in the feedback and refinement processes also felt that the most important decisions focused on things they had handled during the project. It is possible that they chose to modify the parts of the design that they had already put so much work into, and therefore placed higher value on those parts. It's also possible that there is overlap with ownership bias here, and that participants felt more attached to the decisions that impacted their direction the most. Lastly, it is also important to note that effort (hours) and feeling "heavily invested" were only significantly correlated for customer needs analysis ($\rho = 0.385$, p = 0.02, n = 36) and the economic analysis ($\rho = .637$, p = .000, n = 36). This means that there was no true consistency for what it meant to be heavily invested in parts of the project. Being "heavily invested" is likely a more internal, subjective measurement relative to the rest of one's team and one's work on other phases, while effort (hours) provides a more standard measurement of work put into the project.

5.4.3 Availability Bias

For availability bias, there was a search for instances in which decisions or opinions were developed based on an ease of obtaining or recalling information. The first search was with respect to how participants viewed the market of their chosen problem. There are two reasons for this approach. First, it is possible that those who believed they are a part of the market would have a more positive perception of it than those who are not. Second, it would be interesting to see how the opinion of the market change over time, as more information became available to them and incorporated into the project. The four statements assessed, which were asked across each of the five surveys, are shown below.

- "There is a large market for this product."
- "The market is niche, with only a specific set of end users that would be interested in purchasing the product."
- "I am part of the potential market for this product."
- "This product would be a disruptive innovation if introduced to the market."

The initial survey of market perception showed a significant positive correlation between "There is a large market for this product" and "I am a part of the market for this product" (Spearman's $\rho = .411$, p = .013, n = 36). This remained a significant correlation for all remaining surveys [Survey 2: $\rho = 0.349$, p = .037, n = 36] [Survey 3: $\rho = 0.397$, p = .016, n = 36][Survey 4: $\rho = .394$, p = .019, n = 35][Survey 5: $\rho = .477$, p = .003, n = 36]. This means that for the entire semester, participants who believed they were in the market had a higher impression of the market for their design idea than those who did not. The case for availability bias is that participants more strongly believed in the market being large if they were a part of it.

An additional strong, negative correlation was found between being in the market and believing the market was niche [Survey 1: $\rho = -.542$, p = .001, n = 36][Survey 2: $\rho = -.347$, p = .038, n = 36][Survey 3: $\rho = -0.468$, p = .004, n = 36]. This means that participants who felt they were part of the market were less likely to believe they were inside a niche market. This statement is less true for the later part of the semester, as the correlation did not hold for the final two surveys (that is, for everything after concept selection: prototyping, user feedback, design revisions, economic analysis, and final report). It is possible that with more information, the participants were willing to admit that the market was different than their prior beliefs.

Lastly, for market perception, it was investigated whether participants who felt like they were in the market were actually contributing towards gathering more information during the process. One significant, negative correlation was found between being heavily invested in the customer needs process and believing that they had purchased products in this market before ($\rho = -0.343$, p = .041, n = 36). This means that participants who believe they have purchased products in the market before were *less likely* to be as invested in the needs gathering process. This implies that those who felt more familiar with market and problem space were progressing under their own idea of the needs (readily available information in memory), rather than seeking out information that would deepen their understanding.

Outside of market perception, another avenue explored for availability bias was through the stakeholder chosen for customer needs assessment, as well as the user feedback stage. The following statements were asked after gathering customer needs (Survey 2) and user feedback (Survey 4), with participants providing their level of agreement in Likert scale format.

- "They were the most available set of people."
- "They may not necessarily be the best depiction of our market."
- "They were exactly the users we wanted to target."
- "I would have needed more time to collect data from the people I wanted to include."
- "I would have needed more resources to collect data from the desired population."
- "I was aware that one or more of the subjects had previous knowledge or feelings about the problem."

Statistical analysis of the responses shows strong correlations between agreement that stakeholders were not the best depiction of market and agreement with needing more time

(Customer Needs: $\rho = 0.497$, p = .002, n = 36; User Feedback: $\rho = .478$, p = .004, n = 35) and needing more resources (Customer Needs: $\rho = 0.517$, p = 0.001, n = 36; User Feedback: $\rho = .362$, p = .033, n = 35) to interact with their desired stakeholders. The case for availability bias is that the information driving customer needs was largely the most available information, rather than the best representation of the market. Unlike the market perception results, in which participants may not be aware of their bias, these correlations make it appear as if participants were aware that the information they were receiving from stakeholders was not ideal and may have led to misinformed decision making.



Figure 5.4 – Comparison of the perception of stakeholders used to gather customer needs versus user feedback.

Figure 5.4 provides the number of participants that somewhat or strongly agreed with these statements regarding stakeholders consulted towards customer needs and user feedback. The purpose of this is to compare any differences in perception of the stakeholders consulted for customer needs compared to user feedback. At least 80% of

participants believed they consulted the most available set of people for extracting customer needs (32 participants) and user feedback (29 participants), while agreement that the stakeholders were exactly who they wanted is much lower at 55% for customer needs (20 participants) and 43% for user feedback (15 participants). Additionally, at least one third of participants for each task admit that the stakeholders may not be the best depiction of their market.

The data appears similar for both the customer needs assessment and the user feedback process, with the user feedback process leaning slightly more towards an availability bias. "They were exactly the users we wanted to target" received the biggest decrease from survey 2 to survey 4, and there were increases in needing more time and admitting that the stakeholders may not be their best market depiction. However, there were no statistically significant differences to report between the two phases. It should be noted that the user feedback process had unforeseen barriers, as this took place after students were placed in virtual learning for the pandemic. It is possible that without these unforeseen circumstances, participants would have learned from their stakeholder selection in customer needs and adjusted as necessary for user feedback. Regardless, the stress and crunch time that the end of the semester provides may have also played a role.

Lastly, Table 5.6 breaks down the number of team members who somewhat or strongly agreed that their stakeholders were the most available, yet also not necessarily the best market depiction. Teams 9 and 10 appeared to struggle more than the other teams with regard to access to stakeholders, and this can be seen in the Survey 5 reflections of participants from both teams. These statements are provided below Table 5.6.

	Customer Needs	User Feedback
Team 1	1	1
Team 2	2	1
Team 3	1	0
Team 5	1	0
Team 6	1	1
Team 7	1	1
Team 8	1	1
Team 9	1	4
Team 10	2	3

Table 5.6 – Team members who agreed that the stakeholders targeted were the most available but not necessarily the best depiction of their market.

Participant 9.1: "Going online for COVID was difficult, which we could not see coming. Lack of physical prototyping made it hard to evaluate specific aspects of the design. Aside from COVID, originally we pursued a portable design which we found out from feedback was not viable, so we redirected our project to a stationary structure."

Participant 9.4: "Maybe customer feedback [encountered issues requiring adjustment or reassessment of design direction]. No, [issues encountered were] because of the coronavirus."

Participant 10.3: "We struggled with getting well-rounded feedback for the second user survey and our communication started to get sparse once the online class started. It led to extra time being used where it wasn't needed but we made it work. Communication over GroupMe was always a little sparse but we were good with meeting when we needed to so I saw it coming but I knew we would still get it done." Participant 10.4: "I would have liked more time to evaluate our final concept design. There wasn't enough time at the end of the semester to gather user feedback on the chosen design."

5.4.3.1 <u>Summary</u>

This section has contributed insight into the market perception of the participants, particularly towards participants who felt that they were closer to the market, as well as how this perception changed over time. There was a consistent correlation between being a part of the market and believing the market to be large; however, the negative correlation between being a part of the market and feeling the market to be niche lost significance in the final two surveys. It is possible that an availability bias diminished across the semester as new information was received. However, this could also tie into framing bias: a "large market" can be viewed as a positive framing of the market, and a "niche market" could be viewed as a negative framing of a market. Participants seem reluctant to let go of the positive frame of their market, although were willing to give some agreement to the negative framing. Additional correlations showed that participants who felt that they were a part of the market did not feel as invested in the customer needs process. This may show that participants were biased towards the beliefs they already had easily available if they were less willing to actively search for new information.

Lastly, a comparison was performed for how participants viewed their stakeholders used for customer needs assessment and user feedback. There were similar results for both sets, with large percentages of participants believing their chosen stakeholders were the most available and not the most representative of their market. This means the information received from these sessions may be perceived as biased based on availability. However, it is important to note that participants realize that this is the case. This information was used to pinpoint two design teams which may have consulted the most available stakeholders, and therefore the more available information, to make critical decisions about their design direction.

"This product would be a disruptive innovation" Survey 5

Status Quo Bias

5.4.4



Figure 5.5 – Likert responses for how students perceived the innovation of their product.

To look for status quo bias in the student design teams, participants responded with their level of agreement with the following statement: "This product would be a disruptive innovation if introduced to the market." As shown in Figure 5.5, belief in the product being innovative never surpassed the percent agreement received after the initial project selection

(Survey 1). It is possible that participants settle into a more status quo role as the semester progresses. This could be due to several factors, such as the difficulty of the semester, fatigue within the team and project, or realizing that initial goals would be much harder to meet with the time and resource constraints of a course. There is a steep drop from Survey 3 to Surveys 4-5, which may imply that the circumstances of the pandemic forced teams to reevaluate their expectations for the project.

Across five surveys, there were 62 total responses that disagreed that the product was innovative. This data was cross referenced with the satisfaction survey question responses found in Figure 5.2. Only 5 times did the participant disagree with both the product being innovative and being satisfied with the corresponding decision making at that point in the project. In other words, when participants did not believe their product to be innovative, 92% of the time they were still satisfied with the process or decisions made by the team. This could be a case for status quo bias, as those who do not believe their product would be innovative are still satisfied with their results. Three of the five responses that were not satisfied were from participant 2.3, and all three participants (5 responses total) used Survey 5 reflections to express displeasure with the project selected, stating this as the one thing they would have changed about their project. An example reflection statement from each of these three participants is shown below.

Participant 2.3: "I believe this product is niche at best and has potentially no market. The price point is insane. I would've changed the focus of the project entirely."

Participant 8.3: "I probably would have chosen a design problem that I was more passionate about. Some of my friends in other groups chose problems relating to their personal lives or jobs and it seemed they put more effort into the outcome of the project. However, my team chose our design problem because it was one that the majority agreed upon."

Participant 10.1: "I frankly did not love our design problem... there were too many competing products already on the market which made any of our "innovations" feel pointless. It felt like we were redesigning the wheel on many aspects of the project. I would've spent more time to identify a more innovative and interesting problem to tackle. However, in these kinds of group settings, I've learned it's often not worth that level of time investment."

Table 5.7 below breaks down the data from Figure 5.5 at the team level. This table shows the number of team members (out of four total) per team that agreed their product was innovative, at the time that the surveys were completed. From this data, we can see that Team 1 has the lowest number of team members buy into the innovation of their product, averaging less than one person per survey. However, Team 1 also did not produce a single "disagree" response when it came to satisfaction at each project deliverable, and only three responses were rated "neutral" satisfaction. Multiple Team 1 members expressed how their product was not the most innovative in the Survey 5 reflection data, shown after Table 5.7. It should be noted that Participant 1.4 did not complete Survey 4. One participant from Team 5, which was among the highest scoring teams on average, indicated that their team really pushed the boundaries of what they could achieve within the course.

Table 5.7 – '	Team members who agreed that the product would be a disruptive
innovation.	The table highlights the teams with the highest (green) and lowest
(yellow) ave	rage agreement.

	Survey 1	Survey 2	Survey 3	Survey 4	Survey 5	Average
Team 1	1	2	0	0	0	0.6
Team 2	3	2	3	3	2	2.6
Team 3	1	1	1	1	1	1
Team 5	4	3	4	1	1	2.6
Team 6	0	2	2	1	1	1.2
Team 7	2	1	1	1	1	1.2
Team 8	2	1	1	0	1	1
Team 9	3	1	1	2	1	1.6
Team 10	1	1	2	1	1	1.2
Average	1.89	1.56	1.67	1.11	1.00	

Participant 1.1: "I would say that a more radical change to an umbrella would be worthwhile. I don't think we would have had enough time to do this though."

Participant 1.2: "I would change the decision to focus on the phone mount. We made this decision because it was the first applicable idea, but we should have asked the customers what they would have preferred."

Participant 5.4: "I would have started with a more feasible idea from the beginning. We wanted to go for a wild concept, then all of our customer feedback was that it was unfeasible."

Some demographic personality data may also provide insight into status quo bias. Participants were asked their agreement with the following statement: "Usually, the solution that exists to a design problem (the status quo) is a good one." There was a statistically significant trend between agreement with this statement and satisfaction with the concept selected. The more likely a person is to believe that status quo solutions are typically good ones, the more likely there were to have been satisfied with the concept chosen by the team to move forward ($\rho = 0.378$, p = 0.025, n = 35) and less likely to believe a better concept was left on the table ($\rho = -0.360$, p = 0.033, n = 35).

In addition to using the perception of innovation as a measure of status quo bias, the perception of the target specifications was assessed as well. Survey 2 asked participants to list what they believed to be the three most important design specifications for their project. This was asked immediately after the benchmarking, customer needs, and design specifications portion of the project. These specifications were ranked by each student in order from most important (Spec 1) to third most important (Spec 3). The statements asked to each student can be found in Table 5.8.

Results were analyzed to identify if participants were choosing specifications that were easy to hit or appropriate for the class, but would not separate the design from competing products. Spearman's correlation was performed across the seven statements for each level of specification (most important to third most important). Only once did a correlation occur with the specification separating the design solution from competing products and the other six statements. For Spec 3, there was a positive correlation between the specification being likely to meet one or more customer needs and being likely to separate the design from competing products ($\rho = 0.392$, p = 0.018, n = 36).

	Somewhat / Strongly		
	Agree		
Survey Questions	Spec 1	Spec	Spec
		2	3
I agree with the use of this target specification.	36	36	35
It will be easy for the team to meet this target specification.	27	25	22
The specification is a proper target to aim for in this class.	34	33	32
The specification will definitely meet one or more of the customer's needs.	36	34	33
The target specification will separate our design solution from competing products.	21	25	23
This target specification will be easy to ideate solutions for.	21	23	19
I am the one who identified this specification.	15	15	12

Table 5.8 - Number of participants in agreement with target specification statements (N = 36).

There were two additional strong, positive correlations from this analysis. If the specification was seen as easier to meet, then it was also more likely to be considered easy to ideate solutions for (Spec 1: $\rho = 0.595$, p = .000, n = 36; Spec 2: $\rho = 0.624$, p = .000, n = 36; Spec 3: $\rho = 0.720$, p = .000, n = 36). For Spec 1 and Spec 3, more agreement with being easy to meet the specification correlated with more agreement that the specification was an appropriate goal for the class (Spec 1: $\rho = 0.486$, p = .003, n = 36; Spec 3: $\rho = 0.508$, p = .002, n = 36). These correlations are logical in the sense that specifications that are easier to meet would fit within the time constraints of the semester and not require much effort to identify a solution that meets the specification. Therefore, it is not likely that these correlations contribute towards the presence of status quo bias. However, 75% of

participants believed their most important specification would be easy to meet, and that percentage decreases with each specification of lower importance. Although not statistically significant, it is worth considering if participants, whether consciously or subconsciously, decided to rate easier specifications as more important or not.

Table 5.9 breaks down the number of participants per team who somewhat or strongly agreed that the specifications would separate their design solution from competing products. The average number of participants in agreement across each of their top three specifications was calculated as well. The results show that Team 1 noticeably had the least amount of agreement that their most important specifications would separate their solutions from the competition, with Team 5 having the most faith in their designs. Overall, Participant 10.1 was the only participant who put somewhat or strongly disagree for each specification, and this frustration was shown in the Survey 5 reflection mentioned earlier in this section.

	Spec 1	Spec 2	Spec 3	Average
Team 1	0	1	1	0.67
Team 2	4	3	2	3.00
Team 3	3	3	3	3.00
Team 5	4	4	4	4.00
Team 6	3	3	3	3.00

Table 5.9 – Team members in agreement that the target specifications will separate their design. The table highlights the teams with the highest (green) and lowest (yellow) average agreement.

Table	5.9	Continu	ed
Lanc	J./	Continu	i u u

Team 7	2	2	2	2.00
Team 8	2	4	4	3.00
Team 9	2	3	1	2.00
Team 10	1	2	3	2.00

5.4.4.1 <u>Summary</u>

From the results above, a case for status quo bias is collectively shown through participants that were heavily satisfied with their project without belief that their product is innovative, in addition to that belief in innovation decreasing over time. At the team level, it was shown that Team 1 had the least belief in their product being innovative, yet they showed no dissatisfaction during the semester. This makes the case that Team 1 had the highest level of status quo bias during the semester. This is backed by Survey 2 data showing that Team 1 had the least faith in their specifications separating their design from competing products. Team 5 had some of the highest belief in their product being innovative, as well as their target specifications separating their solution from the competition. Survey 5 reflections show that while the team did push for a wild idea, they had to settle for a more feasible result. However, one team member (participant 5.4) did not seem as thrilled that the team was pushing the boundaries of the problem space.

Future work should seek to dive more into the relationship between rating a specification as important and rating a specification as easy to achieve. The methodology should be reworked to understand exactly why belief in innovation decreased through the

semester. It should also consider that a certain amount of status quo bias may be a good thing for course projects. As Hu and Shealy note, "status quo bias is a heuristic that persists because overcoming it demands more cognitive attention and resources [27]." There is benefit to status quo bias to set realistic expectations for course-based projects. However, it is worth understanding how to push some limits while setting others in a design course setting.

5.4.5 Confirmation Bias

5.4.5.1 Customer Needs

Participants were asked in Survey 1 to list what they believed would be the top 5 customer needs of their problem. In Survey 2, after their customer needs assessment, participants were asked to list what they individually believed to be the top three customer needs for the problem. Figure 5.6 helps to understand if there was confirmation bias in what the participants individually listed as their top three customer needs. The figure conveys how many of a participant's top three needs in Survey 2 were carried over from their initially predicted needs in Survey 1. Additionally, it compares how many of a participant's top three considered of high importance by the team in the team's customer needs assessment submission, in which needs were ranked high, moderate, or low importance. For example, only seven participants provided a set of top three needs in Survey 2 that had zero similarities to their initially predicted set of needs, and two participants had all three needs in Survey 1 appear in their Survey 2. This implies that either these two participants either had a firm understanding of the problem beforehand, or they

were unwilling to let go of their prior beliefs, a case for confirmation bias. Determining if a need appeared in Survey 1 and Survey 2 for an individual was done through an inter-rater process with two researchers, resulting in a Cohen's kappa of 0.7.



Participant's Top Three Customer Needs

Figure 5.6 – This figure shows the number of top three needs personally predicted by the participant in Survey 1, as well the number of needs also considered high importance by their team.

There was a series of evidence suggesting that while the teams collectively came to a consensus on importance rankings, individuals did not let go of their pre-existing beliefs. For example, only 10 of 36 participants listed three needs that were all considered high importance by their team, with six participants submitting zero needs considered high importance by their team. Nearly 50% (24/50) of Survey 1 "predicted" needs duplicated in Survey 2 were not considered "high importance" by their team. For nine participants (25% of participants), every personally predicted need they included as a top three need was not considered high importance in the team rankings. Lastly, three participants used at least

two of their own predicted customer needs, and zero of the team's "high importance" customer needs. The authors did not find any demographic data that explained the results of this data. However, it was shown that the method by which needs were generated played a factor in repeating customer needs. Individuals were statistically significantly more likely to include their own predicted customer needs in the top three when their teams used interviews over surveys to gather information from stakeholders (H(2) = 8.081, p = 0.018).

Figure 5.7 shows responses to statements asking how the needs assessment impacted the participant's view of the customer needs and the design problem overall. The statements have been listed in their full form below.

- "The customer needs analysis confirmed my belief regarding the validity of the problem."
- "The customer needs analysis altered my belief regarding the validity of the problem."
- "I became aware of new customer needs I did not previously consider."
- "The customer needs analysis confirmed the customer needs that I was aware of beforehand."
- "The customer needs analysis portrayed some of my initial thoughts for customer needs as not relevant or important."



Impact of Customer Needs Assessment

Figure 5.7 – Survey statements describing the perception after the customer needs assessment.

Figure 5.7 shows that 31 participants (86%) agreed that new customer needs were provided that were not previously considered. However, zero participants disagreed that the process confirmed their beliefs about the validity of the problem as well as the needs they were aware of beforehand. This could be a case for confirmation bias, as the resulting new information did not change their prior beliefs. However, it is likely that framing bias is occurring in some form with this data set. When asked whether the analysis altered their beliefs about the problem or initial customer needs, there was a more even distribution across Likert scale responses. Therefore, the impact of confirmation bias is likely to be smaller. Five participants disagreed that their initial beliefs about both their problem and needs were altered in some way. Only two of these participants belonged to the same team (Team 9).

5.4.5.2 First Solution Ideas

For the concept selection process, it was investigated which participants or teams held onto some of their first ideas about their design solutions. In Survey 1, after the participants had formed their design problem, participants were asked to predict their first idea of what the solution would look like. This was asked again in Survey 2 after customer needs assessment and target specifications were completed. These predictions were compared to the team concept selected to move into the user feedback phase. The relevant survey questions are stated below.

- Survey 1: "In no more than 2 sentences, describe your first idea of what the solution will look like."
- Survey 2: "After identifying customer needs and target specifications, in no more than 2 sentences, describe your current idea of what the solution will look like."

To compare the concept selected and the survey responses, features were extracted from the text-based descriptions of team preliminary concepts, submitted by each team as a class assignment. An example set of features is shown below with Team 9:

Table 5.10 – Team 9 features in their preliminary concept selected.

Team 9 Features
Wheels
Collapsible legs
Modular panels to switch modes (spray/sandblast)
Pull-down front cover hood
Tapered hood top
Ventilation from the back
Multiple, Replaceable filters

In this example, two researchers independently looked at the eight individual survey responses (four from Survey 1, and four from Survey 2) and made a decision about whether these features were explicitly noted in their responses. The two researchers did this for 3 of 9 teams assessed (Team 10 was not included, as they had not yet reduced their ideas to a single concept by the end of Survey 3) and reached 95% agreement (133/140 matches). Then, one researcher continued coding the remaining teams. To strengthen the case for confirmation bias, the results were filtered for features found in both Survey 1 and Survey 2, with multiple teammates predicting the feature at least once. There were five such features, listed below.

- Team 2: Shreds and scans bioplastics
- Team 5: Rail loading
- Team 6: Finger jointed box design
- Team 8: Modular "Lazy Susan"
- Team 9: Modular panels to switch modes (spray/sandblast)

Survey 5 reflections were again used for additional insight. Team 5 appears to have been actively pushing a big idea they had at the beginning of the semester. Team 6 had one participant express displeasure with the ideation method and believed that their team did start with a solution in mind. Team 8 has one participant show confirmation bias unknowingly by stating that they did not have to adjust direction much in the process, and a Team 9 participant believed that the lack of ideas smothered their potential. The reflections imply that some participants were aware that the team started with a solution in mind, some realized it later in the semester, and some had no concerns about what they did. These reflections are shown below.

Participant 5.2: "The initial design goals of completely redesigning aircraft interiors was a bit ambitious given the scope of the semester. It likely would have been more reasonable to adjust our focus to a single one of the customer needs, such as decreased boarding time or increased passenger space. We likely should have seen this coming, but it was also a good opportunity to explore a unique design concept with relatively low risk."

Participant 5.4: "I would have started with a more feasible idea from the beginning. We wanted to go for a wild concept, then all of our customer feedback was that it was unfeasible."

Participant 6.2: "I would have proposed more designs that were not modular. We started with a solution in mind, and I think it would have been better to remain solution neutral."

Participant 8.1: "We didn't really have to adjust or reassess the direction of our design..."

Participant 9.3: "The biggest problem I had was the truncated ideation process, as I am used to a more drawn-out process that forces the design team to view the ideation from multiple angles, developing a more comprehensive overall design. It wasn't a problem with the design, just with the total amount of ideas developed for the design."

The team problem statements can also provide more context to the appearance of confirmation bias. Team 8 references a Lazy Susan design in their problem statement as a current solution, which may have led them to be biased towards a modular Lazy Susan.

Team 6 referenced modularity in their problem statement, and they show bias towards a certain modular design in their solution. It also appears that Team 5 moved towards confirmation bias in their problem space by referencing modularity (a removable cabin) as the solution for their problem.

Team 5 problem statement: "...Being able to load passengers and cargo before a plane's arrival with a modular interior would save airlines time and money by reducing downtime. The team proposes a lightweight, modular seat that can be adjusted for flight duration and class. In addition to the seat, a removable cabin is proposed to expedite the boarding/deplaning process, interior maintenance, cleaning, and seat reconfiguration for optimized aircraft performance."

Team 8 problem statement: "...Current products include spice racks and Lazy Susans, but these still require the user to search through all the spices to find the one they want..."

Team 6 problem statement: "...Our product addresses these needs by bringing to the market a cat toy which is interactive, can be tailored to individual cats, and modular so that segments can be replaced or built upon. The concept is discovered by design-by-analogy when looking at tunneling systems that have been developed for hamsters."

5.4.5.3 User Feedback

For what they considered to be their top three decisions after user feedback, participants gave their agreement to the following statements:

• "This decision led to design concept(s) refinements."

• "The decision was based on feedback that altered my beliefs about the design concept(s)."

There were very few decisions listed that did not lead to design concept refinements. 89% of the most important decisions led to changes, along with 83% of decision #2 and 77% of decision #3. The table below shows the number of participants who somewhat or strongly agreed that the decision was based on feedback that altered their beliefs about the design.

	Decision #1	Decision #2	Decision #3
Team 1	2	2	2
Team 2	1	1	0
Team 3	3	2	3
Team 5	3	2	3
Team 6	1	3	1
Team 7	2	2	2
Team 8	0	1	0
Team 9	4	3	3
Team 10	2	0	1

Table 5.11 – Agreement that the decision was based on feedback that altered their design beliefs; teams with low agreement across decisions are highlighted (yellow).

Teams that rarely had members admit that their views of the design changed have been highlighted in Table 5.11. The case for confirmation bias is that these teams had at least half of their members believe that the most important decisions made after user feedback were the ones that agreed with their prior beliefs about the design. Team 8 did not have a single person believe the most important decision after user feedback was a decision that changed their beliefs. Three participants specifically (2.2, 5.3, and 6.4) listed decisions that confirmed their beliefs and also did not require design changes. Two of these participants commented on the feedback process in Survey 5 reflections. One blamed the communication issues that began through working from home, while another believed it to be an insufficient set of users that provided feedback.

Participant 2.2: "One issue was understanding what each other was thinking when making design changes. It was definitely difficult with not being able to do most of this in person. This is not something we could have seen beforehand because no one could have ever imagined that everyone would have to begin working from home."

Participant 6.4: "I would survey a more diverse user group. Due to convenience, we mostly surveyed graduate students, but I think it would have benefited our design process if we had surveyed a group with a more diverse income distribution."

5.4.5.4 Economic Analysis

For confirmation bias in the economic analysis, participant perception of profitability was investigated using the following statements from Survey. These statements are followed by the combination of responses in Table 5.12.

• "The analysis confirmed my beliefs about the strength of the final design to be profitable."

• "The economic analysis suggests the final design must be improved for profitability."

	Agree that the analysis	Disagree that the design	Participants who gave
	confirmed their beliefs	must be improved	both responses.
Team 1	4	1	1
Team 2	3	0	0
Team 3	3	1	1
Team 5	4	3	3
Team 6	4	2	2
Team 7	1	1	0
Team 8	3	3	2
Team 9	3	2	2
Team 10	2	2	1

Table 5.12 – Economic analysis survey responses regarding design profitability.

It is interesting that for eight of nine teams, at least half of the members believed that the analysis confirmed their beliefs regarding profitability. For teams with a higher number of participants who also believed the design did not need improvement to be profitable, there is likely a deeper explanation beyond forms of confirmation bias. Based on the Survey 5 reflections, Team 5 members may have believed they had too many factors to consider for this analysis to alter their beliefs. For Team 8, three team members took issue with the teammate who led the analysis. These examples are provided below.

Participant 5.3: "It is hard to identify which additional factors might change the validity of our economic analysis at this stage of the design process. I think those factors and their

impact would become more apparent in detail design (i.e., after we've solidified the choice of materials and manufacturing processes)."

Participant 5.4: "Unsure how to factor in people getting upgraded to first class."

Participant 8.1: "We assigned the economic analysis part of our report to _____ because he hadn't done very much else during our project... _____ did complete it but made a lot of mistakes and questionable decisions so the rest of us helped _____ find better resources for some of his numbers..."

Participant 8.3: "Only 3 out of the 4 team members actually contributed to the design process. _____ didn't do his section of the report until we forced him to do it at the last minute, which resulted in a weak economic analysis."

Participant 8.4: "During the economic analysis, the initial cost breakdown has certain items out of price range, some due to the miscommunication with the teammates."

5.4.5.5 <u>Summary</u>

This section provides a review of individuals that did not let go of their previous beliefs about the customer needs, despite new needs received during the customer needs analysis and the team consensus putting other needs as more important than one's own predicted needs. The type of method used to identify needs also played a statistically significant role in holding onto prior beliefs towards customer needs. A coding process searched for features predicted by participants before the concept ideation phase that made it into their chosen design concepts. It was shown that some teams may have started with solutions from the beginning, as seen in their problem statements. Multiple teams included modular features that were imagined in the problem statements originally. These results warrant future work in addressing a separation or relationship between confirmation bias and design fixation [103]. While it is possible that participants preferred certain solutions from beginning to end, having these initial ideas also may have made it more difficult to look for a diverse field of ideas.

A review of participants that believed the most important decisions after user feedback were ones that confirmed beliefs already held before feedback. These results were shown at the team level to understand which teams may be suspect to confirmation bias rather than feedback that may change their design direction. Lastly, self-reported survey scores after the user feedback phase showed which participants had their beliefs confirmed about product profitability without requiring major design revisions. This was shown at the team level to see how many teams might have been using the economic analysis as a confirmation rather than a critique.

5.4.6 Ownership Bias / Endowment Effect

5.4.6.1 Value of Customer Needs Generated

To examine ownership bias, one area investigated was how participants would take ownership of the customer needs generated. Ownership bias would suggest that participants placed higher value on customer needs that they generated over needs discovered by other team members. The data for this assessment includes:
- Survey 1 responses asking participants to generate up to five customer needs that they believe will be important for design success.
- Survey 2 responses asking participants to list what they believe to be the top three most important customer needs, after the customer needs assessment has been performed.
- Team assignment submissions that include the full set of customer needs generated, complemented by a ranking for each need (high, moderate, or low importance).
- Survey 2 Likert scale responses concerning the participant's market perception.

A strong positive correlation was found between the number of one's own predicted needs (Survey 1) ranked within the individual's top three customer needs (Survey 2), and the Likert scale survey responses for the following statements (Survey 2): "I am a part of the potential market for this product ($\rho = 0.395$, p = .019, n = 35)" and "I have purchased products in this market ($\rho = .401$, p = .017, n = 35)." This means that participants who ranked more of their own predicted needs as one of the top three most important needs were significantly more likely to consider themselves a part of the market or to have purchased products in the market previously. This could be interpreted as participants taking ownership of the customer needs because they had a better grasp of the market before the project began. However, out of 21 participants who somewhat/strongly agreed that "I am a part of the potential market for this product", 62% (13 participants) included at least one preconceived need that the team submissions did not include as high importance (eight participants had two of such needs). This means that almost two-thirds of participants who considered themselves a part of their design project market placed

higher value on the needs they personally generated compared to the team collectively. This can be considered a case for ownership bias, as the participants are attributing increased value to needs they "own" because they believe they are a part of the market, and have ownership over the customer needs.

5.4.6.2 Ownership of Design Deliverables

In Survey 2, participants were asked to list out what they considered to be the top three most important customer needs and target specifications. In Survey 3, participants were asked to list their favorite three ideas generated by all individuals on the team. For each of these items, participants provided Likert scale responses to whether they were the person who generated or identified the need, specification, or idea. The number of participants who agreed with this statement (somewhat or strongly agree) is listed in Table 5.13.

Survey Questions	Agreement			
Customer Needs	Need 1	Need 2	Need 3	
I am the one who identified this customer need.	15	15	14	
Target Specifications	Spec 1	Spec 2	Spec 3	
I am the one who identified this specification.	15	15	12	
Idea Generation	Idea 1	Idea 2	Idea 3	
I came up with this idea.	11	17	22	
I contributed greatly to generating this idea.	21	20	24	
I had no role in generating this idea.	9	6	8	

Table 5.13 – Agreement with ownership of top needs, specifications, and ideas generated.

The results show that 42% (15 participants) agreed that they identified what they believed to be the top customer need, as well as the most important target specification, and 58% (21 participants) believe they contributed greatly to the best idea generated. This could be a case of ownership bias as a clear majority participants believe that they contributed to generating the best concept for their designs.



Figure 5.8 – Percentage of participants who included a certain number of their own ideas in the list of best threes ideas generated.

Figure 5.8 shows a breakdown of participants based on how many of their own ideas were included in their list of the top three ideas generated within the team. A significant negative correlation was found with the number of one's own ideas listed in the top three and feeling satisfied with the concept chosen ($\rho = -0.375$, p = 0.024, n = 36). So, those who listed more of their own ideas as top three ideas were less satisfied with the final concept. They were more likely to believe a much better concept was left on the table ($\rho = 0.464$, p = 0.004, n = 36), and they also were less likely to be satisfied by the ideas presented

by teammates ($\rho = -0.591$, p = 0.000, n = 36). This is an example of ownership bias, as participants who value their own ideas the most also felt that their teammates produced ideas of lesser value.

5.4.6.3 Ownership of Successful / Unsuccessful Decisions

For Survey 5, participants were asked to describe one decision critical to the success of the design, as well as one decision that they would change if possible. They were also asked whether they were influential in those decisions or not. Survey responses were categorized based on how participants assigned credit to the decisions made. Two researchers coded 25% of the data, with a 100% agreement rate, with one researcher categorizing the remaining data set. Two example responses are followed by the categories for responses (Table 5.14) and the categorization results (Figure 5.9). Two participants did not list an unsuccessful decision, so there are only 34 responses for this question.

Team Decision: "The decision to switch from rollercoaster style seating to smart overhead bins. The design was considered infeasible and based on remaining time would have been complicated to sufficiently realize. The decision was made as a group, although I feel that with additional time, the concept could have been properly developed."

Self Only Decision: "I think the lead screw aspect was critical to the design success. In the feedback from experts, they were very interested in this as it prevents having someone to have to manually turn the pile and saves time, manpower, and increases safety. I thought of the idea and was very influential in adding it to the design."

Category	Definition
Team, Self-	The participant assigns credit/blame to the team as a whole, but they
Emphasis	also emphasize/specify what they uniquely contributed compared to
	other team members.
Self and	The participant assigns themselves credit/blame for influencing the
Member	decision, as well as another specific team member.
Member	The participant only assigns credit/blame for influencing the decision on
	another team member.
Team	The participant only assigns credit/blame for influencing the decision on
	the team as a whole, and see themselves no more than equally influential
	as other team members.
Self Only	Participant assigns only themselves credit/blame for influencing the
	decision.
Does not	The participant does not make it clear who has influenced the decision.
Say	

Table 5.14 – Categories for assigning ownership to successful/unsuccessful decisions.

Assigning Influence to Critical Decisions



Figure 5.9 – Assigning influence to critical decisions.

The figure shows that for decisions labeled successful, participants tend to assign themselves credit in some form. This was not the case for the decisions that participants would like to have modified – only seven responses mentioned themselves specifically as influential in some way, compared to 19 times in successful decisions. Almost four times as many decisions were credited as a general team decision when it was considered unsuccessful versus successful. These results could be considered ownership bias because participants are either assigning decisions they owned as more valuable than other important decisions, or they are taking more ownership of decisions than they should, simply because they saw those decisions as valuable. Successful decisions saw more references to oneself rather than the team as a whole.

5.4.6.4 <u>Summary</u>

Overall, the ownership bias assessment showed that participants who felt they were a part of the market were more likely to value customer needs they were aware of before the customer needs assessment, despite their respective teams neglecting to give those needs a high importance ranking. These results may be comparable to Zheng and Miller, where individuals took ownership of ideas that other team members felt had low goodness [55]. Individuals in this study took ownership of customer needs that did not receive as high of value at the team level.

Nearly half of participants assigned themselves credit for generating what they felt to be the most important need and specification, as well as the top idea generated for the final concept. The more that participants felt that their ideas were the best three ideas, they were statistically less likely to feel satisfied with the concept selected. While Onarheim and Christensen show that individual ownership bias can be overpowered when the number of individuals contributing to the decision increases (crowd reliability), the design teams in this study only had four members, making any ownership bias likely more empowering in the decision making process [56]. This study could improve in future work by assessing how ownership relates to the final concept chosen, rather than one's preferred top ideas. However, ownership bias is valid whether one's concept is chosen or not, because it is an internal perception of heightened value.

When asked to assign credit to what participants felt to be the most successful and unsuccessful decisions, the participants tended to not assign themselves as much credit for unsuccessful decisions relative to successful ones. The data is limited by the number of people who did not clearly provide direction towards who was responsible for the decision. Roughly one third of the responses did not provide credit for their decisions. Another modification could include asking for the decision making reflections after all deliverables, to ensure that participants are not biased in what they can recall at the end of the semester. Spreading this data across the semester may also help reduce factors, such as worry regarding final grades, which may be driving bias towards giving oneself credit for good decisions. Lastly, in relation to previous work on ownership bias and gender, these results did not deliver any significant differences between men and women [54].

5.4.7 Hindsight Bias

To identify hindsight bias, three open-ended questions were asked in the final survey:

- "In 2-3 sentences, describe one major decision about the design or design process that you would change if you could do the project over again. Why did you/your team make this decision? Were you influential in making this decision? What would you have done differently?"
- "In 2-3 sentences, describe one major decision about the design or design process that you believe was critical to your design success. Why did you/your team make this decision? Were you influential in making this decision?"
- "In 2-3 sentences, describe any issues you encountered in your design process during the semester. This can be any difficulties that required you to adjust or reassess the direction of your design. Do you believe you should have seen this/these issues coming beforehand? Why or why not?"

The phases of the project where participants considered their team to be unsuccessful, successful, or saw other issues encountered was assessed. After reading through the responses, one rater developed the categories, shown in Table 5.15, that most accurately represented the types of responses given. An inter-rater process was performed where a second rater assigned 25% of the responses to the 10 categories. This is resulted in 93% agreement (25/27 responses). Based on the resulting categorization found in Figure 5.10, the categories "specific concept/feature selected" and "ideation/selection process" were the largest two categories for both successful and unsuccessful decisions. From the participant responses, it is clear that the ideation and selection phases of the project resonated the most in terms of how successful the project was viewed. There could be several explanations for this observation. First, it may be easiest for participants to associate credit or blame to the tangible object they have converged upon rather than the phases, such as setting the problem or customer needs, where a larger design space still exists. Similarly, the success/failure of a specific feature or concept may be the most strong in the participant's mind for Survey 5, as they have only recently completed the user feedback process and refinement. This could make it more difficult for participants to see farther back in the semester to earlier design tasks. Lastly, as many participants had their ideation/selection process interrupted due to the pandemic, it's possible that they remember the important decisions they had to make with respect to such a unique situation.



Phase for Decision Making

Figure 5.10 – Design Task relevant to major decisions that participants reflected upon in Survey 5.

Category	Definition			
N/A	Does not fit into any of the below categories.			
Project Selection	Refers mainly to the project chosen for the semester.			
Customer Needs Assessment	Refers mainly to the needs generated or the process for that			
Benchmarking and	Refers mainly to the benchmarking and generation of target			
Target Specs	specifications			
Concept Ideation/Selection Process	Refers mainly to the process of ideation and concept selection, including methods or decision making processes			
Specific Concept/Feature Selected	Refers mainly to any ideas or features selected through the concept selection process.			
User Feedback Process	Refers mainly to the user feedback process which includes prototyping the concept selected and sharing that with users for feedback			
Design Iteration	Refers mainly to any time the key decision was to modify or change an original decision made by the team.			
Economic Analysis	Refers mainly to the economic analysis of the product			
Detail Design	Refers mainly to a more detailed decision about the product after the concept / feature has been decided, such as material.			

Table 5.15 – Phases used to separate Survey 5 reflection questions.

For the "Issues Encountered", many responses were not applicable to a specific design phase or task due to being directed towards issues surrounding the pandemic or general team dynamics. Example participant responses for successful decisions, unsuccessful decisions, and issues encountered during the semester are shown below.

Successful Decision (Concept Ideation / Selection Process): "Performing the SCAMPI method and coming up with 5 designs from ideation process was critical for our final design. Gathering team's 20 ideas and narrowing down with SCAMPI method and voting process was important in selecting a final design product."

Unsuccessful Decision (Benchmarking and Target Specs): "I would increase the ventilation power. We determined this around the OSHA specifications, but I think we could have made it higher for more effective purposes. This would be easier to see with real testing. I was somewhat influential in that I helped determine this as a target specification."

Issues Encountered (N/A – COVID-19 Related): "I don't think that we really had any issues other than issues that arose because of the COVID-19 pandemic. Dealing with talking over virtual meetings was occasionally difficult and we had some technical difficulties. I don't know if we could have predicted that virtual meetings would have been difficult because I think it was hard to predict that we were going to be in a global pandemic situation."

For categorizing whether participants felt the "issues encountered" should or should not have been seen coming, there was 100% agreement between two coders on 25% of the responses. Most participants (20) did not respond to this portion of the question, although eight participants said they should have seen it coming, and another eight said that they do not believe they could have seen the issue beforehand. Overall, two design teams had three of their four participants respond that they should have seen their issues coming (teams 5 and 10). An additional example from each of these two teams can be found below. Participant 10.4: "We ran into problems when trying to choose between several viable concepts. We should have foreseen these issues and dealt with them using the methods learned in this class, which took us a little too long to realize."

Participant 5.2: "The initial design goals of completely redesigning aircraft interiors was a bit ambitious given the scope of the semester. It likely would have been more reasonable to adjust our focus to a single one of the customer needs, such as decreased boarding time or increased passenger space. We likely should have seen this coming, but it was also a good opportunity to explore a unique design concept with relatively low risk."

Survey 5 also included a set of statements (Table 5.16) for the following prompt: "Looking back on the decisions made during the semester, is there anything else you would have done differently?" Participants responded to these statements using a 5-point Likert Scale ranging from "strongly disagree" to "strongly agree." Table 5.17 breaks down the responses to these statements by team. This table highlights in red where teams had more than two participants strongly or somewhat agree with the statements. There is a grey color where teams had exactly half of their participants agree with the corresponding statement, and a green color when there was less than half agreement.

From the table, we can see that Q5, Q8, and Q9 resonated the most across all teams. This includes giving themselves more time to ideate, more time to iterate after user feedback, and more risk taking to produce an innovative product. We can also see teams who may have had regrets across the entire project versus teams that felt satisfied with their process. For example, Teams 2 and 8 never had more than half of their members agree with one of the statements, and only once did they have two of the four members agree. On the other hand, Teams 1, 7, and 10 had over half of their members agree with three of the nine statements. Lastly, it can be seen that Teams 5 and 7 had at least two team members agree with over half the statements (5 of 9).

Question	Statement
Q1	I would have preferred a different problem space.
Q2	I would have revised our method for generating customer needs.
Q3	I would have placed emphasis on different customer needs.
Q4	I would have given our team more realistically attainable design specifications.
Q5	I would have given myself more time to ideate.
Q6	I would have preferred a different concept for the final design.
Q7	I would have voiced my opinion more about critical decisions I disagreed with.
Q8	I would have made more modifications to the design after the user feedback.
Q9	I would have taken more risks to make the final design more innovative.

Table 5.16 – Survey 5 reflection statements on decisions across the semester design project.

	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9
Team 1	2	1	1	0	4	1	0	3	3
Team 2	1	2	1	0	0	0	1	0	0
Team 3	1	0	0	1	1	1	1	3	2
Team 5	0	0	3	1	2	1	2	2	2
Team 6	1	1	0	0	2	0	0	1	0
Team 7	0	2	0	1	4	2	0	3	3
Team 8	1	1	1	1	0	2	0	0	1
Team 9	1	1	0	0	3	0	0	2	1
Team 10	1	0	1	1	4	0	0	3	3

Table 5.17 – Participants per team that "strongly/somewhat agree" with each statement, visually moving from green to red as team agreement increases.

As a final step of the hindsight bias analysis, these statements were compared to participant responses in prior surveys to understand if this was a true indication of hindsight bias. Correlations were found using a Spearman's correlation on Likert scale data across all participants, not just a particular team or subset. The following correlations were found:

- A negative correlation was found between statement Q3 and responses from Survey 2. The more that participants agreed they would have placed emphasis on different customer needs, the less likely they were to have felt satisfied with the logical reasoning for their customer needs in the first place. ($\rho = -0.359$, p = 0.032, n = 36).
- Strong negative correlations were found between statement Q6 and responses from Survey 3. Those who would have preferred a different final concept were less likely

to have felt satisfied with the concept selected after ideation ($\rho = -.629$, p = .001, n = 36), the reasoning for choosing that concept ($\rho = -.504$, p = .002, n = 36), as well as the criteria for selection ($\rho = -.499$, p = .002, n = 36).

- Strong positive correlations were found between statement Q6 and responses from Survey 3. The more that participants believed they would have preferred a different final concept, they were more likely to agree a better concept was left on the table $(\rho = .651, p = .001, n = 36)$, and would have chosen a more challenging concept though it may have failed ($\rho = .352, p = .035, n = 36$).
- Strong negative correlations were found between statement Q7 and responses from Surveys 3 and 4. The more that participants agreed they should have voiced their opinions more, they were less likely to agree that they advocated for their beliefs towards the concept selection process ($\rho = -.540$, p = 0.001, n = 36), the concept chosen ($\rho = -.472$, p = 0.004, n = 36), and the revisions after user feedback ($\rho = -.379$, p = 0.025, n = 35).

Looking at these correlations, it appears that participants were able to recognize their displeasure for specifics, such as customer needs and design concepts, and the processes for achieving those outcomes, in real time. However, it appears that there is more hindsight bias towards recognizing that they should have advocated more for their ideas and beliefs across the semester. As stated in the Bandwagon Effect analysis, most participants who did not advocate for their ideas or beliefs still felt satisfied with the project outcomes associated with each survey. This may imply that either beliefs in the need to advocate were modified at the end of the semester, a truer sign of hindsight bias, or the satisfaction within the

semester was influenced by the good subject effect – participants who did not want to be seen as the unhappy participant of the group [104]. These results do follow one definition of hindsight bias provided by Kerin, as there was "little or no evidence to predict" that participants would be inclined to wishing they had advocated more [40].

Summary

In summary, there is some data from across the semester supporting the existence of hindsight bias, but there is room for improvement. The processes and outcomes surrounding concept ideation and selection received the most attention from participants reflecting on successful and unsuccessful decisions in hindsight. Some adjustments in future studies should allow participants to elaborate more on to what degree issues were expected or unexpected. It is likely that the reflection questions of Survey 5 should begin with Survey 1 and be expanded/modified across each survey, to ensure certain tasks and outcomes receive the same amount of reflection as others. At the team level, a set of reflection statements allowed for insight into which teams had a significant number of participants questioning their decision making in hindsight. These statements were compared to previous survey responses indicating that participants who did not advocate for their beliefs during the semester likely regretted this at the end of the semester.

5.5 Error Management Discussion

As discussed in the background section, adaptive rationality does not show cognitive biases as weaknesses or errors, but an efficient adaption for survival [11, 21]. This done through heuristics (saving time and resources in exchange for a potentially sub-optimal outcome), error management (acting towards less costly error – false positives are less costly than false negatives), and experimental artifacts (preserving resources or livelihood in an unnatural or unusual environment).

This results of the bias assessment of this study have been framed in terms of error management – how participants may have perceived the costs of using these biases as far less than the costs of not adhering to them. An overview of this is shown in Table 5.18.

Bias	Bias Des.	False Pos.	False Neg.	Cost of FP	Cost of FN
Confirmation	Bias towards	User	User	Low: Design	Moderate:
	decisions	feedback	feedback	needs	Design
	after user	confirmed	did not	improvement	requires
	feedback that	your beliefs	confirm	but sufficient	more
	confirmed	about your	your	for course.	energy,
	design	design.	beliefs.		time,
	beliefs.				resources
					during
					crunch time
					of semester.
Ownership	Bias towards	Belief that	Belief that	Low: Some	Moderate:
	the customer	you are	you are not	needs are	Higher
	needs you	aware of	aware of	met, but not	cognitive
	were	the most	the most	all – design	load to
	previously	important	important	retains some	redirect
	aware of as	needs.	needs.	value.	towards new
	important.				needs.
Effort	Overestimate	Participant	Participant	Low:	Moderate:
	desire to	pushes	does not	Participant	Effort does
	push design	design	push	passes	not result in
	to market	towards	design	course and	profits of
	after course	market.	towards	project ends.	product.
	effort		market.		
	expended.				

Table 5.18 – Overview of biases with respect to error management.

Table 5.18 Continued

Hindsight	Bias towards	Hindsight	Hindsight	Low:	High:	
	believing	belief that	belief that	Perception is	Perception	
	you should	you did not	you did	that you were	the team	
	have	advocate	advocate	not to blame	overruled	
	advocated	enough	enough	for project	you, or that	
	more during	during the	during the	flaws.	you	
	the semester	project.	project.		influenced	
					flawed	
					decisions.	
Status Quo	Bias towards	Satisfaction	Lack of	Low: Project	High: Time	
	satisfaction	with design	satisfaction	ends with	and energy	
	with design	project	with design	course	diverted	
	solutions	progress.	project	completion.	away from	
	without		progress.		other	
	innovation.				semester	
					tasks	
Availability	Overestimate	Market is	Market is	Low:	High:	
	market size.	perceived	perceived	participant is	participant	
		as larger	as smaller	not required	would exert	
		than is	than it	to push	considerable	
		actually is	actually is	product to	energy to	
				real time	refocus	
				market	design	
					space.	
Bandwagon	Bias towards	Not	Advocating	Low:	Moderate:	
	satisfaction	advocating	for your	continuing	potential	
	with the	for your	beliefs or	project with	backlash or	
	majority	beliefs or	ideas.	good morale	conflict,	
	opinion	ideas.		and	more time	
				chemistry	committed	
					to decision.	

The table offers a new perspective of heuristic decision making. Rather than the perspective of saving time and resources, it is framed as choosing the less costly error. For example, effort bias shows that participants are more likely to state that they will pursue further development of the design after the semester if they invested more time into several 147

parts of the design process. This bias shows an overvaluing of the design. To the participants, it would be less costly for them to consider pushing to market and having it fail, rather than to not pursue a product development and miss out on a profitable opportunity that they have invested a lot of effort into. The availability bias in terms of heuristics allows participants to save time and resources by going with the most available information, even though it may not be the most optimal information. In terms of error management, participants may decide that the costs of having a misperception of the market is lower than the costs associated with the additional effort they would have to put into finding the true market size. There is less future work involved if you believe that you already know there's a market and what that market needs. This may show that while participants who felt invested in the process were aware that the end users were the most available that they could find, but showed no significance with being unsatisfied with the results.

There are other examples for this as well. The bandwagon effect may show that the costs of being satisfied with the majority opinion is much less than going against the grain in a meeting or pushing the team to do more ideation or analysis. Those connected to the status quo bias may need to evaluate if the additional effort towards innovation is worth it when viewing their semester as a whole, their passion for the project, and their course grades. By pushing the envelope, participants had to make a decision about how much mental effort was worth the innovation they produced with their team. Those exhibiting ownership bias with customer needs may believe that they will help the team in the long run by holding onto needs that they believe to be of higher value to the market, rather than

letting the team find out later in the semester that their needs are incorrectly ranked. Confirmation bias in the user feedback phase may ensure that participants get through the fatigue that occurs over time during the course. While the more valuable design was not produced, they may feel that they learned the process and survived the course.

5.6 Conclusion

This study shed light on common biases in student design teams and where/how they may be occurring. The study used real student design project data along with survey responses regarding the student experiences in their teams. After highlighting these biases, a discussion how each bias may fit into the lens of adaptive rationality, particularly in the forms of heuristics, error management, and experimental artifacts.

There are some clear limitations to this study. First, some course deliverables were not specifically submitted through course assignments that could be used to support or rethink our claims. For example, team interview/survey method questions for customer needs and user feedback were not submitted as part of the corresponding class assignment; therefore, only data such as the final set of customer needs and the user feedback process summary were submitted and available for this study. This prevented checks for potential framing bias or confirmation bias in those questions. In future studies, more unstructured data would be needed for additional converging evidence of these biases.

The COVID-19 pandemic also interrupted this semester of data collection, and the resulting redirection of projects, courses, and general lifestyle of each participant may have all been a factor in these results. This is a case study, so the results cannot be generalized

to other cases. However, it can be the basis for future inquiries and targeted design phases for mitigating biases. For example, we can compare the results of a new graduate level engineering design course with methods in place to avoid what we've seen in this design environment. Additionally, we can improve the methods used in this study to find the magnitude of the hypothesized biases.

CHAPTER 6. FRAMEWORK FOR THE EVOLUTION OF HEURISTICS IN ADVANCED MANUFACTURING (STUDY IV)

6.1 Introduction

This study focuses on the knowledge gap in understanding how heuristics are perceived by designers, as well as how they are developed through designers' experiences. There is also room for improvement with extraction and characterization methodology. The motivation for this study is to improve the focus from Studies I and II for how heuristics are developed, evolved, perceived and valued. This study contributes to design theory by providing an awareness of how sets of heuristics are modified as designers attack new problems, gain new experiences, and implement new technologies. It also contributes to design methodology from by improving the extraction process from Studies I and II. This study adds a design journal documentation process by participants before moving to an interview phase, and provides a confirmation step during survey completion. Building off of Study III, Study IV aims to expand understanding of how these heuristics are implemented from an error management perspective.

These methods are applied to participants in positions requiring the use of advanced manufacturing technology. Five participants were familiar with the Mazak VC500, a hybrid machine combining additive manufacturing and CNC technology. The additive process is a directed energy deposition (DED) method, where an energy source welds the deposited material to a substrate [105]. Participants engaged in this study with respect to

two versions of this technology: one which uses powder fed deposition, and one with uses hot wire deposition of metal. Three additional participants were familiar with the EOS M280 laser powder bed fusion (LPBF) additive manufacturing machine [106, 107].

Accuracy in documentation of heuristics is beneficial for translating them to new team members and other training processes. This accuracy is especially critical as a foundation for new manufacturing technology in current development. Other series of studies in design have been successful in extracting, then testing implementation of heuristics within the process of novice designers, such as heuristics that guide ideation [108, 109]. Similar work is found as well in heuristics that guide design for additive manufacturing [110-112]. To that end, with this study, the following research questions are addressed: *How do designers perceive their heuristics as they develop in advanced manufacturing? What aspects of heuristics and design environments should be considered during documentation of heuristics for a repository? How might the methodology improve for heuristic extraction and characterization?*

6.2 Participants

This study includes eight participants, including seven graduate students in a manufacturing research lab at a major university, and one recent graduate from this university now employed at a national lab. There were seven men and one woman who participated in this study. Six participants classified themselves as white, with the other two classifying themselves as asian. Seven participants were aged between 21-30 years old, with the remaining participant aged between 31-35 years old. Participants averaged

 4.4 ± 1.6 years of design experience and 3.8 ± 1.85 years of manufacturing experience. For both categories, the highest amount of experience was six years and the lowest was two years of experience. At the time of the study, participants had been in their current positions an average of 2.4 ± 1.03 years, with a max of 4.5 years and a minimum of 1.5 years. All participants had some form of graduate level education in mechanical engineering: two participants had obtained their doctorate, and five had obtained at least a master's degree, with one participant still pursuing their master's.

This was a valuable subject pool with which to study heuristic development due to their needs to create new heuristics and refine their current heuristics to ensure successful builds and satisfactory part quality. This includes everything from designing the part for the machine, to planning the build, troubleshooting the build and assessment the part quality post-build. This knowledge is crucial to passing on to team members, novices, and for their own continuous improvement in maximizing the value of their design process. These heuristics serve as a foundation for translating design processes to newer technologies as well, as the advanced manufacturing technology evolves over time.

6.3 Methods

The methods for this study consisted of a series of two journal entries, two interviews, and one survey for each participant. The journals and interviews occurred over the course of several months, as time was needed for both participants and researchers to produce a successful study. This provided participants time to think through each journal question without significant restrictions on the time allotted for completion. After design journals were completed, time was needed for researchers to produce a preliminary heuristic extraction and scheduling of the interviews based on the availability of each participant. Additional time was needed after interview completion for heuristic refinement and for surveys to be customized for the heuristics of each participant.

6.3.1 Journal One

Journal responses were requested and delivered securely online. Participants were asked to document aspects of their process through a set of prompted questions. Journal 1 asked for responses to a series of ten questions, found in Appendix F. The purpose of this journal was to allow participants to provide how they perceive their general process from beginning to end, regarding their interaction with the manufacturing machine to produce their desired parts.

Questions 1-2 were meant as easy questions to get the participants thinking about their process [113]. Question 1 asked which machine they would be doing the journal for, and question two asked participants to list what they believe the most important parameters and settings for their machine.

As it is possible that the participants did not normally describe their actions as "heuristics", the journal focused on using simple, familiar language and avoiding more formal definitions of heuristics [113]. For example, questions 3-5 asked participants for the "processes/strategies/actions" taken before using the machine, while using the machine, and any exceptions where their listed steps would not be followed. Question 7 asked for "lessons learned" while using their respective machine, and asks for the participant to

imagine if they were teaching someone else how to have success with their machine. Lastly, question 8 asked for "rules of thumb" applied to their designs when considering their specific machine.

The journal was also set up to prompt the participants to view their actions from multiple perspectives. For example, many of the design "rules of thumb" (question 8) may likely be applied "before using the machine" (question 3). Question 6 asked for examples of troubleshooting, which may include actions that the participants did not initially consider in the process or process exceptions. Question 9 asked for how they determine part quality and build success, and question 10 asked participants to list what rules of thumb they use that they have taken from experience with previous machines.

6.3.2 Journal Two

After the first journal was complete, participants moved to Journal 2. Journal 2 asked about the participants' most recent build in an additional set of ten questions, found in Appendix F. The importance of this journal is to once again provide a different perspective for participants to reflect on their own process. Considering a very specific machine use, as opposed to generalizing over many instances, may provide new contexts or actions that were not previously considered in Journal 1. This follows additional guidance from Krosnick and Presser to begin asking general questions about a topic before asking specific and targeted questions on the topic at hand [113].

Journal 2 began with five questions that assisted participants in recalling information about their most recent build. These five questions asked for the overall objective, material used, geometry and rough dimensions, and the values for the key parameters and settings for this build. Questions 6-7 asked participants if any strategies used to plan or perform this build differed from what was documented in Journal 1. Question 8 asked participants to describe any troubleshooting that took place. This was asked to understand if potential troubleshooting issues were not documented fully in Journal 1. Questions 9-10 asked for the results of the build and any insights derived that may impact future builds. This question hoped to find knowledge that participants may be using to develop heuristics for future builds.

6.3.3 Interviews

After both journals were submitted, a first pass was taken at extracting the heuristics in context-action form. These heuristics were taken into the interviews for additional refinement in collaboration with the participants. Two interviews, one-hour each, were performed virtually through Microsoft Teams format and audio/video recorded, then transcribed. One researcher conducted all interviews, prompting participants to talk about their set of heuristics. The script followed by the interviewer can be seen in Appendix G. Through the semi-structured interview format, the interviewer was given freedom to focus the questioning on aspects considered important to adding more clarity to the heuristic, how it was formed, or the justification for its use [114]. However, the format for each interview can be broken down into three different sections, discussed below.

The first section of the interview was dedicated to explaining the purpose of the study and helping the participant understand why they were completing these design journals. This was followed by a more formal definition of a heuristic, as previously defined by Fu et al. [5]. The purpose was to relay to the participant why the information asked for in the design journals could be considered heuristic information, that the researchers then rephrased into context-action form.

The second section was the largest portion of the interview sessions. At this point, the interviewer presented the participants with their first pass at developing context-action heuristics from the design journals. A series of questions were then asked to the participant in an effort to get more insight into the heuristic and to improve its presentation. The questions asked the participant to:

- Decide whether the heuristic is an accurate depiction of how they perceive their process
- Provide an explanation for choosing this heuristic in their process
- Provide how this heuristic came to be in their process
- Provide any alternative actions that could have been taken
- Provide any key criteria that may be considered when choosing this heuristic

Several follow-up questions were asked as needed by the researcher, using the semistructured format. This was performed for heuristics found across all design journal data, starting with the processes before and during use of the machine, and moving on towards heuristics in regard to troubleshooting, lessons learned, design rules, and part quality. A final portion of the interview lasted about 15 minutes per participant at the end of the second interview. This questions asked participants to speak more generally about other aspects that may have impact on how heuristics are formed or documented. Participants were asked to:

- Describe how experience with other machines impacted their process
- Describe how they currently document their heuristic knowledge
- Describe the areas where they wished they had more strategies or intuition
- Describe how their process has been impacted by: advisors/supervisors, team members, formal education, and industry standards.

6.3.4 Surveys

After interviews, heuristics were modified as necessary for survey creation and distribution. Surveys were then distributed online through Qualtrics, gathered through webbased submission. The survey was broken into two sections. The first section asked for demographic information, such as age, gender, degrees earned, manufacturing/design experience, and how long they have been in their current position. The second section began with a Likert scale confirmation of heuristics taken from each individual's journal and interview data. Then, additional characterizations of the heuristics were requested, such as:

- Origin of heuristic and the process stages in which they are applicable
- How often and how long each heuristic has been used
- Reliability and evolution of the heuristic in their own process
- Additional factors contributing to whether they choose to implement the heuristic
- Reasons why the heuristic helps maximize the value of their process

• Additional descriptions of how they view their heuristics

Several guidelines from Krosnick and Presser were followed in the development of this survey [113]. For example, the survey begins with questions of low difficulty. Participants were also asked one question at a time, with similar aspects, such as origin of the heuristic, applicable stages of their design process, etc. grouped together. Surveys used wording familiar to participants, and heuristics were specific to each participant. Having processes tailored to each individual should increase motivation to fill out the surveys as accurately as possible. Lastly, it is possible that this method has reduced some recall error, as participants have already began reflecting on their process in the journal and interview process.

6.3.5 Heuristic Extraction

Similar to previous studies, the coding process began with matching context and actions together within the design journals [115]. The interview process clarified or refined those context-action pairings, or added new contexts and actions to the set. For many aspects of the design journals, there was a clear enough context-action pairing to set up a preliminary heuristic for the interview sessions. An example of this extraction process is shown below.

6.3.5.1 Example One

Journal Question #3: Document any planning processes/strategies/actions that you typically go through before using this machine. Please be as thorough as possible.

Participant Response: "Most of the hybrid components we manufacture at **** are done using a CAM software called HyperMILL. The first thing to do is to import your CAD model into the software (Or design it using HyperMILL's native CAD)."

Extracted Heuristic: Before using the machine, first import your CAD model into HyperMILL (or design it using HyperMILL's native CAD).

These heuristics formed through the journals were then discussed in more detail in the interview session. The interviewer asked questions as they considered necessary to uncover more relevant information about each action. In this example exchange shown below, enough new insight was found to refine the preliminary heuristic, while adding two new heuristics to the set.

Interviewer: "Is there any benefit to you for choosing to design it in the native CAD versus doing it in another program yourself and then importing it?"

Participant: "There is benefit to doing it in the native CAD/CAM software. So, it kind of depends on how competent each user is. You know, a lot of people know SolidWorks/Fusion, so they feel a lot more comfortable drawing parts up there. But you do it in the native CAD/CAM space when you're using the same program to design the part and do the toolpath planning. If you don't need to move the part, so you're not trying to transcribe data, you don't have to import/export models. You keep track of features and surfaces and faces, so you know like when you take an STL model, if you if you start in SolidWorks, you may export something as an STL. And STL is just a mesh file so you lose some of the native features that you designed in SolidWorks. You can also just make

changes on the fly. So let's say you're designing apart with a certain cylindrical feature. If you need to change the diameter of that feature, you can just do it in the same program. You don't have to start over from scratch, change it, export it, import it, do the toolpaths. That would be the main reason."

Interviewer: "So ultimately, if you do it in a different place such as SolidWorks or Fusion you're likely going to make some additional changes because things have gotten lost in translation."

Participant: "Exactly. You have data loss."

Interviewer: "...And do those other CAM packages typically work well with the Mazak? *Participant:* "It depends on what you're doing...In the world that I deal with in hybrid manufacturing, not every CAM package offers additive manufacturing. And each package kind of has a different level of expertise. So for example, Fusion: if I was doing a very simple geometry that only requires three axis, you know very something very simple, I would use Fusion. I can do it quicker and easier. But if I'm doing something very complex, I would want to go into Hyper Mill. It's a little more robust, but it's not as user friendly."

Refined Heuristics:

- When developing your CAD model, use the native CAD package for ease of editing and to avoid data loss through importing the model.
- When working with simple geometries, use Fusion to develop the CAD model quicker/easier.
- When working with complex geometries, use Hyper Mill for a more robust CAD model development.

6.3.5.2 Example Two

When the interviewer presented a heuristic to the participant, the participant most often verbally agreed that the heuristics were a part of their process. Therefore, most heuristics were only modified through the additional lines of questioning. However, in some instances the participant realized that some information was missing. In this example, the participant realized that an "essential" step was not included in their design journal.

Journal Question #3: Document any planning processes/strategies/actions that you typically go through before using this machine. Please be as thorough as possible.

Participant Response: Mazak Hybrid System: The first step is to set up a work coordinate system of the substrate, I would be printing on.

Preliminary Heuristic: Before using the Mazak machine, the first step is to set up a work coordinate system of the substrate used for printing.

Interviewer: "So, the first thing you said was before using the Mazak machine, the first step is to set up a work coordinate system of the substrate used for printing. Does that sound like an accurate depiction of how you perceive that part of your process?"

Participant: "Yeah, I did leave out one thing – I guess picking out the workpiece as well would be an essential step as well. Like cutting it to the proper size and selecting what material that you're wanting to use, but that's going to depend on what you want to print. So like if you have this material, print on this workpiece. For example."

Interviewer: "Ok and that depends on the material that you are going to use."

Participant: "Correct."

Interviewer: "Could you explain why it's necessary from the machine standpoint to set up with the work coordinate system with your workpiece."

Participant: "So the main importance is to make sure that you align, and especially with hybrid, that you align your part with your additive toolhead and your subtractive toolhead. The thing is that the additive toolhead is actually offset with the machining toolhead...you can potentially print in an entirely different area than you wanted to, if you just used someone else's work coordinate system. Worst case is you actually crash into the part. So it's very important to do the work coordinate system first, and set up your workpiece into the system."

Extracted Heuristics:

- Before using the Mazak machine, the first step is to set up a work coordinate system of the substrate to align your tool heads.
- When selecting the work piece, choose the substrate material based on the material being used for printing.

6.3.5.3 Example Three

The connection of contexts and actions was not always clear in the design journals. In some cases, the participant would write a phrase with no clear direction. Consider the rule of thumb from one participant below, followed by the interview exchange. The interviewer had to probe the participant as necessary without an initial heuristic present.

Journal Question #8: List your most common rules of thumb that you apply to your designs when designing parts for fabrication on this machine.

Participant Response: Layer height of the beads.

Interviewer: "You wrote a line that I wanted a little more clarity on, you just said 'layer height of the beads.' I wasn't sure exactly what you were referring to?"

Participant: "OK, So what layer height is, say this is one bead...You'll notice that usually the first layer actually has a different layer height then the other heights as you build more...So what we do is we just take an average and get the average layer height per bead. So this would be one layer, two layers and three layers."

Interviewer: "Do you need that value as something critical to produce the build?"

Participant: "It's definitely necessary because as you as you build taller and you do not have the proper layer height. Say for example you have too low of a layer height, so it's actually smaller than it should be...What happens is as you build taller, this distance gets further and further, so your parameters will actually change and vice versa. So you have too much of a layer height, so you predicted that if it's too tall, like say you have a very large layer height then actually what will happen is this will grow taller. But if it's like too small of a layer height this will actually get closer and closer until you might hit collision into your part. So ideally, if you can get a proper layer height as you build it, you should have a consistent distance between your laser and your printed bead.

Interviewer: "Is that something that you can calculate beforehand, or something that you need to run a few lines before you know what that's going to be?"

Participant: "Yeah, it's not something you could calculate."

Extracted Heuristic: When setting the layer height of the beads, use an average of the first few layers to account for height differences.

6.4 Results

The goal of the journal and interview process was to produce a quality set of extracted heuristics which can then be characterized through the survey method. The results section will focus on the results and analysis of survey data. The discussion section will overview any other insight towards heuristics found during the interviews, as well as an assessment of the journal and interview process as a whole.

6.4.1 Survey Results

After the journal and interview extraction process, participants confirmed in the survey whether the resulting heuristics were used in their own process. This was a Likert scale response shown in Figure 6.1. Out of 126 heuristics, only four were listed as "somewhat disagree", and no heuristics were listed as "strongly disagree." These four heuristics have since been taken out of the additional study survey analysis. It is unclear
how these were invalid heuristics, as there was no follow-up discussion as part of the research study. It can be noted that three heuristics were taken from journal responses that required additional information to develop the heuristic, similar to "Example Three" in the previously described heuristic extraction process.

Confirmation of Heuristics



Figure 6.1 – Confirmation of heuristics used in participant's own processes.



Figure 6.2 – Self-reported origins of heuristics for each participant.

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Figure 6.2 shows participants overwhelmingly listed experience as the main form of heuristic development, which strengthens our definition of a heuristic. It is also not surprising that colleagues provided almost 40% of heuristics given, as these heuristics were developed from the experiences of others in similar contexts. It is also sensible that academic literature appeared in higher numbers than textbook or educational origins, as the participants use these machines for research purposes, and new research is being published consistently on the machine technology.



Combinations for Heuristic Origins

Figure 6.3 – Combination of experience with other origin sources for heuristics (N = 122).

Because 75% of responses included originating from experience, experience is broken down in relation to the other sources as well, as shown in Figure 6.3. It is shown that most heuristics were not listed as just experience only, but from other sources as well. The largest of these combinations was experience plus knowledge from a colleague, followed by experience plus machine specific training. It's possible that while participants were initially given heuristics from other people, they did not consider them part of their own process until they saw the success of those heuristics in their own experiences. For 91 heuristics where experience was listed as an origin, 60 (66%) were connected to "past failures" contributing to their decision to implement that heuristic. Similarly, out of 32 heuristics where experience was the <u>only</u> listed origin, 19 (59%) were connected to "past failures" contributing to their decision to implement that heuristic.



Applicable Stages to Implement Heuristics

Figure 6.4 – Self-reported stages in which heuristics are applicable (N = 122).

Figure 6.4 shows the stages in which the participants labeled their heuristics as applicable. These stages were given in the survey based on the processes discussed in the journals and interviews. It is reasonable that "during build" is the lowest category, as there is little to do for most participants outside of listening and watching for things out of the ordinary. Similarly, the action items after the part has been removed from the machine (post-processing, quality assessment) should be smaller compared the amount of planning,

design, and setup required before machine use, which sets the designer up for the best results on the other end of machine use. Troubleshooting heuristics accounting for more than 20% of heuristics may show how much participants rely on experience to develop heuristics. It may also have implications for the types of information that participants were able to easily recall; it's possible that failures are easily retained, or that participants retain troubleshooting heuristics well due to the importance of proper maintenance and function of the machines to avoid repair costs. As shown below in Figure 6.5, most troubleshooting heuristics are considered to be based on past failures.



Considerations for Heursitics by Applicable Stages

Figure 6.5 – Considerations for heuristics broken down by applicable stages (N = 122).



Figure 6.6 – Self-reported results for how long participants have used their heuristics (N = 121).

Figure 6.6 shows how long heuristics have been used by their respective users. No one put "unsure" for this question, although one participant did skip this question for one heuristic. As stated in the demographics section, participants averaged 4.4 ± 1.6 years of design experience and 3.8 ± 1.85 years of manufacturing experience. Most of the heuristics presented here have been used for 1-2 years. This falls closer to the duration that participants reported to have been in their current positions, an average of 2.4 ± 1.03 years, with a max of 4.5 years and a minimum of 1.5 years. It is possible that participants started these positions with only a small set of heuristics that translated, and built their toolbox over time.

Reasons the Heuristic Helps Maximize Process Value



Figure 6.7 – Reasons that the heuristics maximize the value of participants' processes (N = 122).

In Figure 6.7, responses are shown for which participants checked the ways in which the heuristic maximized their process. They were able to choose across eight factors presented in the survey. The results indicate that participants are more concerned about meeting the requirements of the part than saving time and resources. Another way of seeing this could be that participants see their efficiency in terms of preventing machine failures, rather than successfully saving time, material or other resources.

The contrast between process efficiency and part quality could also potentially be explained across machine users. When comparing EOS to Mazak, 56% of EOS heuristics (27 of 48 heuristics) were characterized as "prevents machine failure", compared to 43% of Mazak heuristics (32 of 74 heuristics). Only ten heuristics were perceived as meeting both perspectives of efficiency: saving the participant both time and material/resources. Nine of these ten heuristics were delivered by the three EOS participants. This may be

interesting in terms of placing value on a "good" heuristic. Being efficient on multiple levels may provide a safety net for using the heuristic and still having success. For example, if the heuristic does not save time during one build, it may still provide efficiency in terms of material used.



Factors towards Implementing the Heuristic:

Figure 6.8 – Factors contributing to the participant's decision to use their heuristic (N = 122).

Figure 6.8 shows a set of seven factors participants could choose from, which describe aspects contributing to the participant's decision to implement the heuristic. Half of the heuristics are associated with input from team members before implementing those actions. Based on interview responses in section three of the interview, all participants explain that they learned the most through guessing and checking, and would talk to team members, advisors, or supervisors to get advice and a general understanding of the machine. Participants trust these heuristics because of their background experience. As participant P8 explains, there is no reason to not trust strategies from other team members

because those members had more experience in that area: "In the absence of any knowledge of it, I guess I have no reason to suspect any of it...especially coming in here to (redacted), I would definitely you know, trust whatever anybody said because I had no experience with it at all...it depends on whether I know anything about the subject or not."

In general, most of the participants explained that textbooks or classroom education has not helped with understanding how to use the machines and troubleshoot. There was a general consensus that formal education helped develop skills for critical thinking and offered an overview of manufacturing processes. However, participants explained that there were no additive manufacturing classes, and most of their knowledge was based on experience. Lastly, participants mostly agreed that they follow the standards available, although they would not consider many standards available to them.

Figure 6.9 shows more characteristics that participants were asked to assign to their heuristics if applicable. It's understandable that the proactive description was associated with more heuristics than the reactive description, as participants consistently implied wanting to avoid crashes or failures that would restart the build or machining process. Only six heuristics total were characterized as risky, and they were all from Mazak VC 500 users. Several of these "risky" heuristics were related to participants making intuitive judgements in the middle of a build:

- For better part quality, run the nozzle closer to the part.
- If the material is over/under building, slow down/speed up the feed.
- If the build makes noise due to significant overbuilding, manually slow down the feed rate and deposit more material in lower areas to even out the part.

Heuristic Characterizations



Figure 6.9 – Additional Characterizations of heuristics (N = 122).

These may have been considered risky because they are relying more on their own intuition on a case-by-case basis. They must trust themselves to hear the right noise, to manipulate the machine to the right speed, to sense where the nozzle works best, etc. This may come with high rewards, but with risk of failure that requires a restart. This is interesting because one way of looking at heuristics is that a "good" heuristic is also "safe" because it is used to produce a satisfactory outcome. It is possible that the participants using "risky" heuristics may not be aware of additional "safe" heuristics to use at this point in their experience level.

Only around 40% of heuristics were noted as easy to recognize the context to apply the heuristic. This visualizes the idea of designers having a heuristic versus knowing when to use it. The participants of this study understand which heuristics they apply, although they still find difficulty in understanding when to implement them. Lastly, as over half of the heuristics were described as performed implicitly, it's possible that participants were able to consider more implicit heuristics with the journal and interview process. The journal method gave participants sufficient time to consider their whole process and from multiple perspectives, and the interview asked them to assess why they made those decisions.

6.4.2 Statistical Correlations

6.4.2.1 Spearman's Correlations

Figures 6.10-12 show the how participants described the heuristics in terms of reliability, frequency of use, and evolution. There were no participants who put "unsure" for "How often does this heuristic evolve?" However, one heuristic failed to receive a completed survey response for each of the three attributes. This certainty in responses may be due to the interviewer constantly asking participants to reflect on how their actions have evolved while using their respective machines. These three survey questions were correlated using Spearman's correlation, with discussion of them following the figures.



Figure 6.10 – Self-reported results for how often the heuristic is reliable (N = 122).

"How often do you use the following heuristics?"



Figure 6.11 – Self-reported results for how often the heuristic is used in their process (N = 121).



Figure 6.12 – Self-reported results for how often the heuristic is evolving in their process (N = 121).



Figure 6.13 – Combination of responses for heuristic reliability vs its frequency of use (N = 121).

Figure 6.13 shows the combination of responses for heuristic reliability and its frequency of use. There was a significant positive correlation between the reliability of a heuristic and its frequency of use (Spearman's $\rho = 0.538$, p < 0.001, N = 121). This means that as the perceived reliability of the heuristics increases, it tends to be used more in the participant's process. Consider the examples below. One reason that increasing the layer size is considered low reliability is because there may be better actions available for the specific case, such as changing the recoater blade type. For a highly reliable action, such as setting the build order from bottom left to top right, this is driven by a machine phenomenon that will be consistent from build to build.

Low Frequency, Low Reliability: If the recoater blade crashes, consider increasing your layer size to decrease the chances of another crash.

High Frequency, High Reliability: When setting the build order, build from bottom left to top right to minimize the impact of metal condensate.



Figure 6.14 – Combination of responses for heuristic reliability vs its evolution (N = 121).

Figure 6.14 shows the combination of responses for heuristic reliability and its evolution. There was a significant negative correlation between the reliability of a heuristic and its evolution (Spearman's $\rho = -0.437$, p < 0.001, N = 121). This means that heuristics considered to be more reliable are also perceived as changing less often. Consider the examples below. It's possible that several factors contribute to the heuristic being less reliable and changing often. These could include: the participant modifying which colors they believe have resulted in better parts, inconsistency in color being a true correlation to material properties, or the criteria for the quality of specific parts fluctuating. For the more

reliable heuristic, the speed of a dry run depends less on the specifics of the build and should likely stay consistent as machine technology stays consistent.

Low Reliability, High Evolution: To determine design quality, check the color of the build for dark burn marks or a rainbow-like color, which can indicate weakened material properties.

High Reliability, Low Evolution: When performing the dry run, avoid going full speed so that you can visually confirm the spots being hit.



Frequency of Use vs Evolution

Figure 6.15 - Combination of responses for heuristic frequency of use vs its evolution (N = 120).

Figure 6.15 shows the combination of responses for heuristic evolution and its frequency of use. There was a significant negative correlation between the frequency of use of a heuristic and its evolution (Spearman's $\rho = -0.382$, p < 0.001, N = 120). This means the heuristics that participants tend to use more are perceived as changing less. As discussed in the previous correlation, the build order is likely used for most interactions on

the EOS M280, as the heuristic is the result of machine specific physics that occur for every build. Consider the set of heuristics listed for low frequency, high evolution. It's possible that over/underbuilding occurs often, but the action chosen to address this is never consistent and is constantly being modified and improved upon. This decision could depend on several factors, such as surface quality requirements, machining availability, confidence in oneself to fix the issue mid-build, or how quickly one notices the issue.

High Frequency, Low Evolution: When setting the build order, build from bottom left to top right to minimize the impact of metal condensate.

Low Frequency, High Evolution: If the material is over/under building, slow down/speed up the feed. If the material is over/under building, change the work offset. If the material is over/under building, and large unevenness of height occurs in the build, machine a few layers, then print afterwards.

For the origin of heuristics, because up to four sources were chosen in some cases, the impact of the number of sources on reliability, evolution, and frequency of use was investigated. Results showed a significant negative relationship between reliability and the number of sources listed for its origin ($\rho = -0.210$, p = 0.020, n = 122). This could be explained as if a heuristic is unreliable, participants are likely searching out other people and resources to help improve that heuristic. However, this is speculation and would require more study of heuristics for which a larger number of sources were listed.

6.4.2.2 Kruskal-Wallis Correlations

The Kruskal-Wallis test was used to compare responses for evolution, reliability, and frequency of use across the other survey response attributes. This is similar to an ANOVA test but for nonparametric data. Therefore, we can judge whether heuristics that obtained certain attributes tend to have more or less reliability and evolution. The results found several significant differences in the data, listed below.

Heuristics with the following attributes were more likely to receive **higher** scores for evolution than those that did not receive these attributes:

- Considered risky, but saves time or other resources (H(1) = 9.671, P = .002)
- Applicable during Mid-Build (H(1) = 12.286, P < 0.001) or Quality Assessment (H(1) = 6.678, P = .010) stages
- Originating from Colleagues
- Factors considered for implementation include input from other team members (H(1) = 8.613, P = .003), or experience with similar machines (H(1) = 4.026, P = .045)

Heuristics with the following attributes were more likely to receive **lower** scores for evolution than those that did not receive these attributes:

- Originating from industry or research standard (H(1) = 9.532, P = 0.002)
- Being a standard form of practice is a considered factor for implementation (H(1) = 20.225, P < .001)
- Listed as unsure of its origin (H(1) = 6.038, P = .014)

Heuristics with the following attributes were more likely to receive **lower** scores for reliability than those that did not receive these attributes:

- The context is easily recognized for application (H(1) = 5.515, P = .019)
- Applicable during Mid-Build stage of your process (H(1) = 3.829, P = .050)

Heuristics with the following attributes were more likely to receive **higher** scores for frequency of use than those that did not receive these attributes:

- Heuristics characterized as performed implicitly (H(1) = 7.558, P = .006)
- Heuristics characterized as valuable because they maintain safety (H(1) = 11.205, P = .001)

Heuristics with the following attributes were more likely to receive **lower** scores for frequency of use than those that did not receive these attributes:

- Literature was listed as an origin of the heuristic (H(1) = 6.250, P = .012)
- Listed as unsure of its origin (H(1) = 3.909, P = .048)

The correlations show that heuristics that were considered risky or applicable mid-build are constantly changing. This is possibly because participants are still trying to figure out the best way to attack those situations. As stated previously, decisions during the build are more so based on how the build is performing and is a case by case intuitive judgement. Therefore, it also makes sense that decisions mid-build were considered significantly less reliable as well. Heuristics originating from colleagues or dependent on team member input are also changing more than other heuristics. These changes may be due to the participant having to adjust input from others to work within their own process. Initial advice may be from a colleague on experiences, but the participant's experience may not line up to be exactly the same. Therefore, the heuristics passed on could require a trial and error process. The opposite seems to be true for heuristics originating from standards or implemented based on standards in place. It makes sense that decisions that appear to be standardized across the industry can be implemented without having to be modified frequently.

Reliability correlations showed that heuristics are used significantly less often when the participant believes the context to apply them is easy to recognize. It is possible that participants remember failures more than successes, and therefore they are able to more easily recall situations where decisions have failed or been inconsistent in the past. The correlations with frequency of use show that heuristics considered to be performed implicitly are used more often than others. This implies that participants do not typically explicitly think about their process in terms of going from one heuristic to the next. Safetybased heuristics are also used more often, showing that participants think a considerable amount in terms of maintaining safety of themselves, their lab members, and the machines that are in use. Lastly, it was found that heuristics originating from academic literature are used significantly less often compared to other sources. It's possible that academic literature is turned to for very specific scenarios and not general processes, and therefore would only be necessary in a few cases. However, this is speculation and cannot be confirmed without additional studies.

6.5 Discussion

6.5.1 Methods Assessment

6.5.1.1 Journal 1

			EOS M280			Mazak VC 500 AM				
Journal Questions	Avg.	St. Dev.	P1	P2	P3	P1	P2	P3	P4	P5
Describe processes before using this machine	4.8	2.4	3	9	6	3	6	6	3	2
Describe processes while using this machine	2.3	2.5	1	2	8	0	2	1	3	1
Describe when you would not adhere to processes	0.1	0.4	0	0	0	0	0	0	0	1
Describe troubleshooting experiences	1.8	1.8	2	0	0	5	3	0	2	2
Describe lessons learned	1.6	1.5	3	0	0	3	0	3	1	3
Describe design rules of thumb	2.4	1.6	5	2	0	2	2	3	1	4
Describe determining part quality/success	2.8	0.7	2	2	3	3	2	4	3	3

Table 6.1 Heuristics extracted per participant based on correlating journal question.

Table 6.1 breaks down the heuristics extracted for each participant based on where it originated in the design journal questions. The visual moves from light to dark gray as the number of heuristics from a question increases. Heuristics were found successfully across questions asking for their process "before using the machine" and "while using the machine." However, there were inconsistencies in how these questions were interpreted. On the EOS machine, the "build order" was discussed by one participant as "before using the machine", and another participant "while using the machine." Similar inconsistency was found in the Mazak participants when discussing the "dry run." Three participants had heuristics discussing the dry run "while using the machine", but one participant included this as "before using the machine." Only one participant did not produce a heuristic "while using this machine." Their response showed that they do nothing outside of troubleshooting besides ensuring the hopper is feeding the powder properly. Participants overwhelmingly presented no new actions for when they would "not adhere" to the processes listed. The biggest explanations were that all steps listed were necessary and required for success. It was suggested that some steps could be relaxed if the part had been printed before, or if the machine was already up and running by another user. Some information was simply reiterated. For example, one EOS participant P1 pointed out that sieving (the process of filtering out larger particles from excess powder recovered from a previous build) was only performed when necessary, but this was highlighted already in earlier portions of the journal. One participant added a note about cleaning the substrates. Only one participant presented information leading to a new heuristic. This Mazak user (P6) noted that they have to re-probe the work offset if the printed part is also going to be machined (the additive and machining heads are offset from each other).

For troubleshooting, the biggest factor on the EOS machine was to prevent recoater blade (mechanism that spreads each layer of powder for fusion) crashes. Even when documenting outside of the "troubleshooting" journal question, a big purpose for many of the heuristics seen was to prevent these types of collisions. For the Mazak, obtaining proper powder flow was the target of many heuristics. One unique perspective (Mazak P7) was not focused on which actions to take to solve known issues, but rather how they attack understanding what the issue is in the first place. For example, when the issue is not immediately clear, this participant focuses on narrowing down their problem to certain critical areas: CNC movement, feed stock, feed rate, and treatment, although these four areas were not defined in more detail during the interview. Only one participant did not successfully write their personal rules of thumb in this section. They listed an example journal article reference containing design guidelines for LBPF [116]. They did not specify which, if any, of those guidelines they used.

All participants successfully listed ways in which they inspect part quality. This includes knowing which methods to use to inspect quality: sometimes it is a technology-based assessment (CMM, CT, etc.) and other times it is a visual inspection.

The full set of heuristics are included in Appendix H.

6.5.1.2 Journal 2

The main point of Journal 2 was to ask participants about a recent, specific build, in order to help participants identify certain strategies they did not catch when completing Journal 1. In regards to this goal, not many new strategies were detected. Participants did not provide any significant changes to the strategies existing in Journal 1. For the EOS M280, all three participants explicitly stated no differences before or during use with the machine. For the Mazak machine, processes were mostly the same as well. Participant P7 relaxed some repetitive tasks based on their comfort level, and participant P8 reused a previous work offset and G-code, making some of their previous steps listed irrelevant. P4 noted they added a laser remelting strategy, but the participant considered the samples unusable and did not state any implications for using this strategy in the future. Lastly, P5 used a different maintenance process for this specific build because a new machine part had been introduced.

Only one new heuristic was added to the set from Journal 2. Participant P1 noted that a "soft" recoater brush might be necessary for future builds with delicate components.

While the build did not produce a "failure", some "struts" were damaged by the recoater action. A soft recoater brush, one that is more like bristles than a blade, would allow the part to respond differently to brush contact.

6.5.1.3 Interviews

Outside of the heuristic extraction examples presented in the methods section, there were several additional, noteworthy interview situations that occurred, which are presented below without examples due to brevity. These include:

- The interviewer asking participants to be more direct regarding vague descriptors in their design journals such as "large" or "unusual."
- The interviewer allowing participants to screen share during the virtual interviews to provide a visual explanation or justification of some heuristics, such as the build order. Participants were not asked to do this, but rather it was done voluntarily by participants who felt that the most adequate justification or explanation would come through visuals.
- Participants provided the interviewer with the concept of learning heuristics by watching others, as shown by multiple Mazak users. These participants both acknowledged that they watch a fellow team member perform troubleshooting and picked things up this way, rather than a verbal or written exchange of information only.

The number of clarifications needed from the journals limited the amount of interview time discussing other aspects with participants, such as how the heuristics came to be. This led to more about context and less about mental processes to reach that decision. The amount of interview time needed per heuristic eliminated the ability to explore more of Journal 2. While it was noted that very few heuristics could be formed from Journal 2 alone, more time would have allowed the interviewer to navigate conversations and probe whether additional heuristics tied to Journal 2 were possible to uncover. This is more of a limitation and tradeoff of the method chosen, as two hours is already a significant amount of interview time and data. A similar sentiment about interview time and method capabilities can be directed towards the key parameters that participants listed in the design journals. While additional information about parameters could have also been obtained through the survey, the survey was sufficiently long enough due to the quantity of heuristics and the amount of questions devoted towards each heuristic. A comparison of parameters across participants may show how each participant forms their perception of what is or is not valuable to their process, although more information from the interview or survey method would be needed to relate this to the value of the heuristics.

The interviewer's lack of familiarity with terminology in interacting with the manufacturing technology may also be an influence in the results of the study. An interviewer with more experience may have saved time by not needing the participant to clarify certain terms, but it is also possible that being too familiar with the process leads to overlooking some necessary questions to uncover key elements of the heuristics. The interviewer in such a situation would be assuming knowledge that the interviewee is not verbalizing because of their own past experiences. An interviewer with more experience in manufacturing may also know what areas to probe during discussion that an inexperienced person may not. However, this influence could also be negative, as it biases the

conversation towards what the experienced interviewer considers important rather than what the participant values.

6.5.1.4 <u>Heuristic Extraction Process</u>

As discussed with Figure 6.1, when participants were asked to confirm that they use the extracted heuristics, only four out of 126 heuristics were listed as "somewhat disagree", and no heuristics were listed as "strongly disagree." It is unclear how these were invalid heuristics, as there was no follow-up discussion as part of the research study. It can be noted that three heuristics were taken from journal responses that required additional information to develop the heuristic, similar to "Example Three" in the described heuristic extraction process. An example is shown below:

Journal Question #9: Describe how you determine if your part has been built successfully. What are the things you look for when determining quality?

Participant Response: "...Depending on the requirements, this could require inspection via hand tools or other metrological techniques (XCT CMM, surface metrology, etc.)."

Interviewer: "You listed ways to inspect part quality, which was CT, CMM, and surface metrology. Are there any of these that you use more than others, or do use these at all for your work? Can you give a rundown of when you would use one over another?"

Participant: "Yeah. So I've used all of those in my research. And each has their own benefits...The last one is <u>computed tomography</u>... CT, however is an extremely complicated measurement procedure. And while it is able to give some pretty awesome results, it is not technically like a traceable measurement technique. So like any

dimensional measurements that you take on a CT have to be taken with, sort of like a grain of salt. That, like we're not actually sure how uncertain we are in this measurement. But that being said, you can still do a number of analyses with it, which are mostly at this <u>point</u> <u>comparative</u>, like you're not able to like take like an absolute measurement of diameter or something like that. But what we've used before is, like you know, <u>comparison of like this</u> <u>process to this process</u>. This part to this part I'm looking at comparisons..."

Extracted Heuristic: To assess quality through point comparison relative to other parts or processes, use CT technology.

6.5.2 Error Management Assessment

As discussed in the background section, Haselton presents three ways in which humans rationally adapt for survival: heuristics (saving time and resources in exchange for a potentially sub-optimal outcome), error management (acting towards less costly error – false positives are less costly than false negatives), and experimental artifacts (a product of poor research design which produces unnatural or unusual environments) [11, 21]. It is possible to view the results of this study in terms of error management – how participants may have perceived the costs of using their heuristics as far less than the costs of not adhering to them.

Previous presentation of results showed that only six heuristics total were characterized as risky, and many of these related to participants making intuitive judgements in the middle of a build: "If the build makes noise due to significant overbuilding, manually slow down the feed rate and deposit more material in lower areas to even out the part." In this situation, the participant must make a decision about whether the costs associated with unnecessarily stopping and manually controlling the build (falsepositive) is less than the costs of letting the build continue and resulting in undesirable part quality (false-negative). The justification for stopping the build would be that more false alarms are better than more misses.

Figure 6.7 showed the attributes that participants attached to heuristics as reasons why the heuristic maximized the value of their process. Near the bottom of the list of valueproducing attributes was to improve efficiency in terms of time (24% of heuristics) and material/resources (20%). At the top of the list, the attributes attached to the most heuristics were to achieve desired part dimensions (56%), to achieve other aspects of part quality (50%), and to prevent machine failure (48%). From an error management perspective, a false-positive would be to spend extra time/material to ensure there is no detriment to the part or machine quality, although the resulting build session shows that the extra time/resources were not necessary. A false-negative would be to save time/material and have a situation occur where the machine or part quality diminishes. The data from Figure 8 implies that participants likely consider the costs of the false-positive to be far less than the costs of the false-negative. In other words, their efficiency is seen through preventing subpar machine or part quality, rather than preserving their own time and resources.

Statistical correlations showed that heuristics characterized as maintaining safety were applied significantly more than other heuristics. From an error management perspective, participants may believe that the costs of implementing a safety based heuristic without it being needed (false-positive) is less than the cost of not implementing the heuristic and safety being compromised (false-negative). In the false positive, additional time and resources may be used, but this cost does not compare to costs that may threaten the health of the machine or its users.

It is possible to see some error management perspectives in how the heuristics have been presented. For example, consider the heuristic: "When setting the build order, build from bottom left to top right to minimize the impact of metal condensate." The action in this heuristic is to set the build order from bottom left to top right. However, the justification of this heuristic is to minimize the impact of metal condensate on the part. The participant may understand that taking the extra time to set up a build in this order, no matter how much condensate may actually impact the part, is much less of a cost than producing a separate build order that produces an unreliable part due to contamination.

The interviews contained some conversations in which participants admitted some level of being risk averse. For example, participant P2 agreed that they may have avoided use of supports when they were not as familiar with them. Instead, they would default to modifying the orientation or changing the part entirely. In those situations, the costs associated with modifying the part or orientation may have been less than the costs of choosing the wrong support and having a failed build. Participant P7 admitted to staying closer to the machine when they were afraid of collisions because of past mistakes. In this situation, the cost of staying near the machine and having a successful build (false-positive) is less than the cost of leaving the machine and being unable to intervene when necessary (false-negative).

6.5.3 Additional Interview Insights

6.5.3.1 Current Documentation Practices

Generally, there is little documentation done by participants individually because some information is hard to convey through writing. When things are documented, Participants P4 and P5 used personal notebooks. A lot of the documentation is used to train people. However, due to the lack of documentation, participant P1 explained that it causes inconsistencies. Overall, most of the participants agreed there is a lack of documentation and wish they had a better way of managing the information. Participant P5 suggested that ideally, all of the information documented would be plugged into a machine-learning algorithm to tell people what is causing the error in the system.

6.5.3.2 Desires for Additional Intuition

Participants P1 and P2 wish they had more intuition or strategies for thermal distortion. The participants are currently planning on obtaining this through early commercial solutions for thermal simulations and simulation software. Participant P3 also had difficulty with thermal systems, specifically thermal management because most of the learning has been through guess and check, and leaving the topic to experts. Participants P4 and P8 both have difficulty with geometry, specifically 5 axis deposition and overbuilding, respectively. P4 does not see this aspect as critical to their research, and P8 fixes the parameters after the build has failed. Both P5 and P6 dislike the process of guess and check. P5 wishes there was a database logging the history of the parameters and characterization of the features for that parameter. P6 explains there is a lot of guesswork

and learning through experience and wishes there was a more efficient way to communicate or automate the process.

6.5.3.3 Impact of Prior Manufacturing Experience

Questions within the journals and the interviews asked participants to think about how experience with other manufacturing machines impact their current process. This reflection is a combination of data from journals and interviews, as design journal responses defaulted to speaking more generally about similarities and differences rather than specific rules of thumb. For example, EOS M280 participants noted that they brought with them the importance of cleanliness, cautiousness, planning, and realistic expectations for how "perfect" your part will be. While multiple EOS participants mentioned how fused deposition modeling (FDM) contributes to an understanding of support structures and orientation, one noted a step in complexity in the support structures when moving to the EOS machine. For the EOS M280, support structures not only keep the part structurally sound, but they are also designed specifically to take heat out of the part during the build. The takeaway is that when transitioning to the EOS M280, participants had experience in considering similar important aspects, but were inexperienced with the added complexities.

For Mazak VC 500 AM participants, there were two main themes: comparison to a similar, subtractive only machine (Mazak VCU) and comparison to a similar, hot wire deposition hybrid machine. Two participants noted benefits in using the Mazak VCU first, because it eased their transition through familiarity in aspects such as the operating system, controls, and G-code. Essentially, the only new component was the additive process. The

remaining three Mazak participants referenced the differences in caution and overbuilding between the hot wire and powder deposition machines, but with conflicting reports. For two participants, more caution was required for the wire deposition to avoid overbuilding. The third participant felt the opposite, claiming that the powder DED was more complex and needed more care towards overbuilding. Only one specific heuristic mentioned in the interviews was stated as translating: the concept of starting each layer in different positions and alternating directions. This heuristic originated for Mazak participant P8 on the hot wire machine and translated to their current role on the powder DED machine.

6.6 Conclusion

This study observed how heuristics evolve within expert designers in advanced manufacturing, and how this impacts the value of those heuristics over time. The results of this study provide design teams with a framework for documenting and updating heuristic knowledge as it evolves over time, along with characteristics that may be used to assess the heuristics' value to the design process. This research provides the following important contributions to the field of design theory and methodology:

- A heuristic extraction methodology that emphasizes corroboration with designers, verifying their use of documented heuristics
- A novel assessment of how designers perceive their own heuristics, based on their documentation, justification, and evolution over time

This study provides the field of manufacturing with a methodology for obtaining and characterizing heuristics, which is beneficial as new technology, such as hybrid manufacturing, continues to grow and evolve. The results show statistically significant correlations between heuristic reliability, evolution, and frequency of use. This validates prior work in heuristics and adds these correlations to the field of advanced manufacturing. The survey results show which attributes given to heuristics statistically significantly impact the magnitude of which heuristic are reliable, evolve, or are implemented into one's process. Lastly, a new perspective of heuristics in advanced manufacturing was shown in which participants' progress towards heuristics that result in the least costly errors.

From a repository perspective, there are limitations to ensuring there are enough heuristics, sufficiently organized, such that they can successfully guide someone through an entire design process and in a variety of contexts. In this sense, the inability to verify saturation of heuristics is a limitation, and additional studies would be necessary to understand which forms of classification would be most beneficial. Additionally, the results are limited in understanding which characteristics studied would be most effective in helping new users choose the correct heuristics and apply them properly. Ideally, the heuristics extracted can be translated outside of the settings studied. However, this is outside the scope of this study. For the heuristics found in this study, translation of heuristics may rely on machine quality and their current technology levels, the experience of the user obtaining these heuristics, or the objectives for the use of their respective manufacturing machine. As expected, case study research generally comes with limited application of results beyond the case being studied. However, these results serve as a starting point for hypothesizing heuristic use across other populations of designers, which can be tested by comparing additional case studies or creating new controlled experiments to test our findings.

CHAPTER 7. CONCLUSION

The main goal of this research was to provide designers with guidance for choosing heuristics adding the most value to their design in any given context. Four studies provided insight into the characteristics of heuristics in design and the methods for extracting them. Study I explored direct corroboration with designers for extraction and characterization of their own heuristics, aimed to correlate heuristic attributes in a manner that visualizes the value they bring to the design context. Study II extracted additional process heuristics from the same design team, in hopes of analyzing how designers perceive their own processes. This study also obtained feedback through a focus group regarding which implementation factors should be considered when building a repository of heuristics for a design team. Study III focused on heuristics from a cognitive bias perspective, observing how heuristics may also be implemented as an error management bias. This perspective was developed through access to graduate design team process data along with course surveys completed through the project. Lastly, Study IV observed how heuristics evolve within expert designers in advanced manufacturing, and how this impacts the value of those heuristics over time. The methodology included a design journal review phase, adding a layer of confirmation to the methodology from Study I. The resulting heuristics were also discussed from an error management perspective. The results of this study provide design teams with a framework for documenting and updating heuristic knowledge as it evolves over time, along with characteristics that may be used to assess the heuristics' value to the design process.

This work is impactful towards a successful prescriptive research phase, as reliable extraction methodologies will lead to reliable descriptions of how designers use heuristics. Moving forward, the described heuristics and their attributes may be used to move towards more normative decision making, ensuring that the designer chooses the heuristic that maximizes the value of their process. From a cognitive bias perspective, there is a need to consider aspects of design thinking that are affected by cognitive abilities and limitations. This research could provide a transformational benefit to society, as cognitive bias is a permeating presence in all human decision-making; a deeper understanding of cognitive bias in problem solving will provide an impact beyond design education.

There are several quantifiable results which can highlight the purpose and importance of this work. For example, in Study IV, 39% of heuristics were perceived as originating from colleagues, and this attribute significantly correlates to heuristics that are perceived to evolve more often. Additionally, 14% of heuristics were described as valuable by maintaining safety, and this attribute correlates to being perceived as used significantly more often in their processes. Participants were shown to lean towards actions with the least costly errors, as 48% of heuristics aid preventing machine failure, compared to 24% said to be efficient in terms of time and 20% efficient in terms of material/resources used. Ultimately, these results are meant to express how heuristic actions have specific characteristics which influence how designers perceive those actions. By bringing those attributes and influences to light, one can begin to more clearly justify the heuristics included in their own process, how they are refined over time, and how they are passed onto other designers.

CHAPTER 8. LIMITATIONS

One limitation of this research is the lack of triangulation to validate that the heuristics extracted portray how they are actually used by the designer. In studies where heuristics are corroborated directly with designers, the designers may have a distorted view of their decision-making. For example, JPL heuristics may be influenced by others in the room, the examples given by the researchers during data collection, or an inaccurate perception of their own processes. Inter-rater agreement validates the extraction method, but not how it is used. Following-up with observations and document analysis after an initial interview / survey could compensate for this. Study IV does use a mixed methods approach that combines interviews with initial observations.

The interviewer's lack of familiarity with terminology in interacting with the space mission design, as well as manufacturing technology, may also have had an influence in the results of the study. An interviewer with more experience may have saved time by not needing the participant to clarify certain terms, but it is also possible that being too familiar with the process leads to overlooking some necessary questions to uncover key elements of the heuristics. The interviewer in such a situation would be assuming knowledge that the interviewee is not verbalizing because of their own past experiences. An interviewer with more experience in manufacturing may also know what areas to probe during discussion that an inexperienced person may not. However, this influence could also be negative, as it biases the conversation towards what the experienced interviewer considers important rather than what the participant values. For Study III, the Covid-19 pandemic also interrupted this semester of data collection, and the resulting redirection of projects, courses, and general lifestyle of each student may have all played a factor in these results. This is a case study, so the results cannot be generalized to other cases. However, it can be the basis for future inquiries and targeted design phases for mitigating biases. For example, we can compare the results of a new graduate level engineering design course with methods in place to avoid what we've seen in this design environment. Additionally, we can improve the methods used in this study to find the magnitude of the hypothesized biases.

From a repository perspective, there are limitations to ensuring there are enough heuristics, sufficiently organized, such that they can successfully guide someone through an entire design process and in a variety of contexts. In this sense, the inability to verify saturation of heuristics is a limitation, and additional studies would be necessary to understand which forms of classification would be most beneficial. In regard to Study II, allowing A-Team members to personally group the heuristics does not guarantee the most efficient repository classification. A similar note can be said for researchers producing a classification scheme in Study I. Additionally, the results are limited in understanding which characteristics studied would be most effective in helping new users choose the correct heuristics and apply them properly.

Ideally, the heuristics extracted can be translated outside of the settings studied. However, this is outside the scope of the performed studies. For the studies involving JPL, it can be hypothesized the process heuristics could translate to design teams better than the artifact heuristics. For users of advanced manufacturing, translation of heuristics may rely on machine quality and their current technology levels. Error management biases may be generalizable more for student teams, and less for those that are more industry-based, expert-led teams. As expected, case study research generally comes with limited application of results beyond the case being studied. However, this dissertation contributes new insight for the use of heuristics which can be apply to future work in controlled experiments to determine generalization.
CHAPTER 9. CONTRIBUTIONS

This research provides the following important contributions to the field of design theory and methodology:

- A heuristic extraction methodology that emphasizes corroboration with designers, verifying their use of documented heuristics. This corroboration was shown in different forms, including individual and group interviews, affinity mapping and design journal documentation.
- A novel approach to characterization of heuristics through the use of surveys, indicating their perceived value to the designer in terms of reliability, evolution, and frequency of use, among other attributes. Statistically significant correlations produced descriptions of when participants may view their heuristics as tending to evolve more/less often, to be more/less reliable, or to be implemented more/less often in their own processes.
- Identification and characterization of the major biases within student design teams, through the designer's personal reflections and access to team design data. These biases were discussed from an error management perspective to understand how their use may be viewed as rational, as it is a decision towards least costly errors.
- A novel assessment of how designers perceive their own heuristics, based on their documentation, justification, and evolution over time.

CHAPTER 10. FUTURE WORK

This series of case studies as exploratory research into the use of heuristics produced findings which can be used to advance future work towards the original research questions of this dissertation.

- 1) How should the methodology for extracting heuristics be improved such that we may assess the value a heuristic brings to the design process?
 - a. Results showed that certain origins of heuristics correlate with statistically significantly higher (and lower) levels of heuristic evolution. It also showed that when participants listed higher numbers of sources, heuristic reliability significantly decreased. The methodology should include an iterative process that includes additional interviews after the survey phase. This will allow more understanding of what information was taken from each source, and the lessons learned from participants using that information.
 - b. The iterative process would also account for corroboration in addressing discrepancies used as a basis for participants not fully agreeing with the final set of heuristics extracted.
- 2) What aspects of heuristics and design environments should be considered during documentation of heuristics in a repository?
 - a. Results showed that some characteristics of heuristics (such as origin, applicable process stages, user perceived characteristics and factors for implementation) imply more evolution over time. This can impact the rate at

which particular heuristics are or should be reassessed and updated in a repository. Staggering the rate at which certain sets of heuristics are updated could improve the efficiency in maintaining heuristic knowledge.

- 3) How might heuristics be characterized and classified to understand their impact on design processes?
 - a. Heuristics should be characterized not only as context-action, but by their sources of origin, applicable process stages, and characterizing descriptors based on perception from previous users. These factors were found to have influence on which heuristics may be more/less reliable or applicable more/less often to the process.
 - b. Heuristics in context-action form should be assessed in comparison to heuristics reframed in an error management form, where decisions are framed in terms of the magnitude in error for choosing or not choosing to implement the heuristic. This will determine which type of framing resonates more with users, or which framing can provide more "successful" decision-making based on the users' measures of success.

These findings can be used as the basis for future testing of the best ways to obtain, document and present heuristics back to their original users, as well as new users in a workplace development environment. These studies would move past the case study phase into a more experimental study phase. For example, future work can test whether an iterative interview/survey process produces more agreement in heuristics than a single interview/survey process. An iterative process may also be used to understand which characteristics of the sources listed as origins are more impactful in the heuristic having higher or lower reliability, evolution, or frequency of use. Additionally, a longitudinal study can be used to judge if a specific staggered approach to updating heuristics is effective, compared to additional approaches to updating repositories. Lastly, new users of advanced manufacturing could be broken into two sets, where one receives information in heuristic form and the other receives information in error management form, to understand how the two approaches might impact design outcomes.

Overall, this work advances the theory of heuristics and the methods for obtaining and characterizing them. It expands understanding of how heuristics are developed and perceived by designers, as well as how they are implemented throughout various phases of a design process.

APPENDIX A. INTERVIEW SCRIPT, STUDY I

- 1. Introductions.
 - a. Reminder about consent form signed they were sent an electronic copy.
 - b. Ask if it's ok to voice record the interview?
- 2. To start off, what is your role at JPL? What is your area of expertise within the A-Team?
 - a. We explain what we are doing and why we are doing it.

What: The purpose of this study is to learn how the JPL A-Team develops design solutions, and what tools and techniques they use. More specifically, we want to identify some of the current design heuristics being employed in early stage concept ideation and during design development for complex systems at JPL.

Why: There is a gap within design research in the understanding of how complex systems are best designed, and the role of design heuristics in that process. We are looking for a more fundamental understanding of heuristics and hope to eventually recommend how and when they are best used in design practice.

- In the future, we may potentially identify heuristics that the A-Team isn't using that could be beneficial to the design process, or assist with using current heuristics in a more efficient manner.
- Having a more thorough understanding of your own heuristics and concept generation technique may help in future training and onboarding of new design team members.

This interview will assist in that process. For us, access to expert level designers is rare, difficult and highly valuable in the research community, so having this opportunity to study your behaviors and practices in design is invaluable to research in design theory and methodology.

- 3. Are you familiar with heuristics?
 - a. If yes: Can you explain what they are in your own words?
 - b. We explain our definition of heuristics.

Heuristic: A context-dependent directive, based on intuition, tacit knowledge, or experiential understanding, which provides design process direction to increase the chance of reaching a satisfactory but not necessarily optimal solution.

More formally, one can think of a heuristic as a combination of a context in which the heuristic is applicable, and a corresponding design action to be considered. A heuristic should thus have the following form: "When in this kind of situation, consider this design action." Some examples:

- c. Example 1 nitty gritty
 - i. "When using a bolt connection, design it to have at least one and onehalf turns in the threads"
- d. Example 2 planning
 - i. Trade Space: Define payload requirements, then design spacecraft based on the payload requirements.
 - ii. For spacecraft design and sizing, first start by preparing a list of design requirements and constraints.
- e. Example 3 systems level
 - i. Power: If mission is to an outer planet, use nuclear power source.
 - ii. Propulsion: If simplicity and low cost are requirements, use cold gas propulsion.
 - iii. Guidance and control: When designing a small satellite to be earthoriented, use a gravity gradient technique for guidance and control.
 - iv. Propulsion: To reach low earth orbit, allow for a delta-v of around 10km/s.
 - v. Payload: In early concept design, estimate the spacecraft dry mass to be between 2 and 7 times the payload mass.

- vi. Risk management: When there are potentially many unknown failure modes, use design redundancies.
- 4. Given this definition, state as many heuristics as you can think of. These should be ones that you have used in the past. Try to think in the context of heuristics you use in your role on the A-Team.
 - a. (Follow up with categories and make sure they explore the whole space, planning, concept development process, trade space analysis, propulsion, power systems, risk management, etc.)
- 5. In general, list the sources/origins of the heuristics. (i.e., experience, education, textbook, mentor, standard of JPL, etc.) Where did these heuristics come from?
- 6. Let's take one heuristic you mentioned and talk more deeply about it.
 - a. Which heuristic do you want to discuss more deeply?
 - b. Where do you use this? Can you give an example of when you used this?
 - c. What part of the design process is this heuristic used in?
 - d. Why / in what situations would you not use this?
 - e. Why is this a good heuristic to use? What characteristics of this heuristic make it more favorable than possible alternatives? What makes it an attractive option?
 - f. What is the origin of this heuristic for you?
 - g. How do you implement this heuristic?
 - h. When did you first start using or become aware of this heuristic?
 - i. How has this heuristic evolved over time?
- 7. Concluding Remarks.

We'd like to send a follow up survey to you asking about the heuristics you listed today. It should only take 10 minutes or so to fill out. Would you be open to responding to our survey?

APPENDIX B.SET OF HEURISTICS, STUDY I

ID	Heuristic
1.1	If the mission involves traveling past Saturn, use a non-solar power source, like
	nuclear power.
1.2	When landing on a body with high gravity, stage the propulsion.
1.3	For a short lived probe, do not use design redundancies in case of failures.
1.4	For an outer planet mission, plan for only X number of instruments to fit on the
	spacecraft.
1.5	For an inner planet mission, plan for only Y number of instruments to fit on the
	spacecraft.
1.6	For spacecraft design that looks similar to a previous design, start with the
	previous design and edit as needed.
1.7	To ensure feasibility, start with a previous design and edit as needed.
1.8	When designing as low cost as possible, start with a design from a previous
	mission that already exists.
1.9	If delta V is below #, use a mono-propellant design.
1.10	If delta V is above #, use a bi-propellant design.
1.11	When delta V crosses a very high # threshold, move to a higher efficiency
	propulsion system.
2.1	To generate ideas in a group setting, write ideas down individually, then combine.
2.2	When deciding what type of funding to seek, use group voting on team ideas.
2.3	When performing a group vote, use a multi vote system rather than one vote per
	person.
2.4	When using a multi vote system, set the number of votes per person to be the
	square root of the total idea categories.
2.5	After a group vote, move forward with those ideas that receive a majority of the
	votes.
2.6	To reduce costs, design missions with the intent to use commercial landers.
2.7	For a larger field of view, send satellites to higher altitudes.
2.8	When launching multiple satellites, use separate launches if the desired satellite
	inclinations are not equal.
3.1	For a deep space mission, consider planetary protection.
3.2	For a deep space mission, always choose components that are completely resistant
	to radiation.
3.3	If the spacecraft is traveling too far from the sun (such as Jupiter), use RTG
	(radioisotope generator) as a power source.
3.4	For a mission with low radiation, generate energy using a Lith-Solar Cell.
3.5	When designing to mitigate risk, consider previous spacecraft designs.

3.6	To mitigate risk during the design process, use margins that account for both
	predictable unknowns and unpredictable unknowns.
3.7	For mission classifications with a cost cap, find the expected mass using the
	expected cost.
3.8	When given the client's objectives, determine the minimum science you want to
	do.
3.9	If the science goals are very well understood, start from an operational scenario
	to find the expected mass.
3.10	For missions with clear science goals, find the expected cost using the expected
	mass required to meet those goals.
3.11	For missions with clear science goals, find the expected mass using the expected
	power required to meet that goal.
3.12	When designing a mission, find the expected power by determining the
	instruments required to meet the science goals.
3.13	To find expected mass, estimate the mass fraction as X% of the power system.
3.14	For spacecraft classifications with a standardized mass, estimate the performance
	using the standardized mass as a starting point.
3.15	When designing a spacecraft, estimate your electrical system to be between X-
	Y% of your spacecraft mass.
4.1	After formulating the science question, follow-up with a hypothesis and
	prediction.
4.2	Break mission knowledge into 4 distinct parts: state-of-the-art, enhancement,
1.2	enabling, and breakthrough.
4.3	When planning the science goals of the mission, bound the mission science in the
4.4	enabling region between enhancements and breakthroughs.
4.4	When deging a proposal, only include the enabling science.
4.5	when designing spacecrait architecture, split the requirements, problems, and
16	Solutions into 5 different oralistorining processes.
4.0	when putting a mission together, address the 8 classical subsystems in the high
17	System. When deciding A team session time allocation break the study into components
т./	and estimate the time for each component
4.8	When planning an A-team session design a study to have between 8-12 people
4.0	For a study with a very high number of participants break into groups for
т.)	hrainstorming
4 10	When delivering cargo to space, estimate \$10,000 per pound to deliver cargo to
	space using present-day rockets.
4.11	When designing a mission, attempt to surpass Voyager's speed by a factor of 10.
4.12	When planning a mission, determine feasibility based on previous designs.
4.13	When choosing the power source, incorporate only one source of power on a
	spacecraft due to costs.
4.14	When choosing the power source, choose based on the mission location.
4.15	When designing a mission, consider solar arrays on a spacecraft first before other
_	power sources.

4.16	When effective sunlight power and viable alternatives are absent, use nuclear
	power.
4.17	For missions at incredibly high speeds, utilize plutonium dioxide for the power
	source.
4.18	For low gravity surface environments, consider cold gas hoppers for mobility.
6.1	For a spacecraft traveling to an outer planet, consider nuclear over solar power.
6.2	For a spacecraft staying overnight on the moon, incorporate 45 kg of batteries onboard to
	ensure survival.
6.3	When designing an orbiter, aim for at least 2 km/s delta v capability to get the craft into
6.4	orbit around a planet.
6.4	When designing an orbiter that requires 3-4 km/s delta v to get into orbit, consider electric
6.5	propulsion.
0.5	kg without an aeroshell and 300 kg with an aeroshell
6.6	For a deep-space spacecraft using solar power, plan to use 200 watts to heat the fuel tanks
0.0	to prevent freezing.
6.7	When designing a mission, design for an expected lifespan of up to 15 years.
6.8	When designing a lunar lander, plan to use 6 watts to survive the lunar night (15 days).
6.9	When designing proposals for missions, replicate successful missions to reassure
	reviewers.
6.10	When designing a mission, consider putting multiple functions, such as an orbiter and a
	lander, onto one element.
6.11	When designing an atmospheric probe, estimate a cost of 150-200 million dollars for a
- 1	weight of 200-300 kg.
7.1	If the mission is not near Earth, plan to be more flexible with your communication system
7.2	requirements.
1.2	If the mission location has a strong environmental force, use a balanced spacecraft to make the attitude control less massive
73	When planning an A-Team study start with an ice-breaker to get the people in the room
1.5	more comfortable.
7.4	For a study to determine the feasibility of a mission, look at multiple concepts.
7.5	If the study involves a very specific mission where a more detailed design is desired,
	focus on just one concept.
7.6	When designing a mission, first determine the science, then the instruments, then the
	mission location, then the flight bus.
7.7	When generating a power system, start with the instruments to determine the watts of
-	power, number of batteries, and kilograms needed.
7.8	For a study concerning one main problem, stay in one large group for brainstorming.
7.9	For a study where the problem is easily subdivided, break into groups to attack each
0.1	subproblem. When planning on A Team study, schedule one his brainsterming session followed by
8.1	when planning an A-ream study, schedule one big brainsforming session followed by multi-voting to parrow the ideas down to three concepts you want to investigate further
82	If it is necessary to run models to determine a concent's feasibility plan the study for 2
0.2	days and run the models as homework between each day
8.3	When brainstorming ideas on sticky notes, plan for the facilitator and study lead to
0.0	categorize ideas.

8.4	When generating figures of merit, use a shout-out exercise.
8.5	When multi-voting, consider how the concepts relate to each figure of merit.
8.6	If brainstorming produces a very large number of ideas, use a two-step narrowing
	process: first have an initial vote, then evaluate remaining concepts using figures of merit.
8.7	When planning an A-Team session, try to cover all 6 colored hats in the de Bono method.
8.8	For cost estimation, assume that half the money flies and half does not.
8.9	For a study with limited information, use the cost rules of thumb as a baseline for cost estimation.
8.10	For a study with a wide range of information, use the CML 2 tool for cost estimation.
9.1	For a successful A-Team study, have an initial client meeting, then a planning meeting.
9.2	When planning an A-Team study, the client meeting should be at least 4-8 weeks before the actual study.
9.3	If the set of ideas generated is not rich enough, combine two sticky notes to create a new idea.
9.4	When planning an A-Team session, make the multi-vote process short so the participants do not overthink their selections.
9.5	During the client meeting, try to determine if homework is necessary for the study, so you can estimate the session length.
9.6	During an A Team study, keep time intervals short to keep the flow going and maximize the amount of things you can get done.
9.7	When presenting topics relevant to the study, keep the presentations short (about 10-15 minutes).
10.1	When estimating delta v, first see if the trajectory has already been done before.
10.2	When estimating delta v, break the problem into chunks, then combine the values for each chunk.
10.3	When estimating a delta v range, stay conservative by adding more overshoot to the upper value.
10.4	If the delta v is too high for chemical propulsion, consider solar electric propulsion.
10.5	If the required delta v is above 3 km/s, move to a special propulsion system that is more efficient.
10.6	If the goal is to transfer from one orbit to another orbit around Earth, use simple energy difference equations to estimate delta v.
10.7	If the mission is to a different planet or asteroid, use the patched conic method to estimate delta v.
10.8	If the trajectory is affected by two different gravitational bodies at the same time, such as a mission at the moon, use sophisticated numerical integration to estimate delta v.
10.9	If the mission involves moons from other planets, try to estimate delta v by applying the patched conic method twice: first using a helios-centered model, then a planet-centered model.
11.1	For concept development, estimate the instrument to be 20-25% of total mission costs.
11.2	To determine the amount of time to schedule for each project phase, stack the proposed timeline against 3 or 4 other missions deemed analogous.
113	When creating schedule reserves, allot more time for the later project phases.

APPENDIX C.HEURISTIC CLASSIFICATION, STUDY I

Primary Area of Concern	Secondary Area of Concern	Action Intent	Example Heuristic
	Pre-Study Planning (12)	Create Schedule / Timeline (11)	When presenting topics relevant to the study, keep the presentations short (about 10-15 minutes).
A-Team		Identify Resources Required (1)	When planning an A-team session, design the study to have between 8-12 people.
(27)	In-Study Facilitating (15)	Idea Generation (6)	To generate ideas in a group setting, write ideas down individually, then combine.
		Concept Selection (9)	When performing a group vote, use a multi vote system rather than one vote per person.
	Design Process Planning (2)	Concept Development (2)	When designing a mission, first determine the science, then the instruments, then the mission location, then the flight bus
	Mission Objectives (4)	Determine Science Goals (4)	When planning the mission science goals, bound the mission science in the enabling region between enhancements and breakthroughs.
	Funding (2)	Create Proposals (2)	When creating a proposal, only include the enabling science.
	Timelines (2)	Schedule Design Phases (2)	When creating schedule reserves, allot more time for the later project phases.
Mission Design (29)	Cost (0)	Estimate Cost (7)	For missions with clear science goals, find the expected cost using the expected mass required to meet those goals.
	Cost (9)	Reduce Cost (2)	When designing as low cost as possible, start with a design from a previous mission that already exists.
	Reliability (7)	Mitigate Risk (3)	When designing to mitigate risk, consider previous spacecraft designs.
		Determine Feasibility (3)	To ensure feasibility, start with a previous design and edit as needed.
		Estimate Mission Lifespan (1)	When designing a mission, design for an expected lifespan of up to 15 years.
	Coverage (1)	Expand Coverage (1)	For a larger field of view, send satellites to higher altitudes.

	Launch System (1)	Define Launch Requirements (1)	When launching multiple satellites, use separate launches if the desired satellite inclinations are not equal.
	Planetary Protection (1)	Determine Requirements (1)	For a deep space mission, consider planetary protection.
	Payload (2)	Instrument Design (2)	For an inner planet mission, plan to fit Y number of instruments on the spacecraft.
		Estimate Power Required (7)	When designing a mission, Find the expected power by determining the instruments required to meet the science goals.
	System Requirements (21)	Estimate Delta-V Required (8)	If the goal is to transfer from one orbit to another orbit around Earth, use simple energy difference equations to estimate delta v.
		Estimate Mass (6)	When designing a spacecraft, estimate the electrical system as X-Y% of the spacecraft mass.
Spacecraft		Power (9)	When choosing the power source, choose based on the mission location.
Design (45)		Propulsion (8)	When landing on a body with high gravity, stage the propulsion.
	Subsystem Requirements (22)	Thermal (1)	For a deep space mission, choose completely radiation resistant components.
		Communications (1)	If the mission is not near Earth, plan to be more flexible with your communication system requirements.
		Attitude & Orbit Control (1)	If the mission location has a strong environmental force, use a balanced spacecraft to make the attitude control less massive.
		Structure & Mechanisms (2)	When designing a mission, consider putting multiple functions, such as an orbiter and a lander, onto one element.

APPENDIX D.SET OF PROCESS HEURISTICS, STUDY II

Primary Category	Subcategory	Heuristics
	Team Building	When setting up an A Team study, make sure you have (1) a facilitator, (2) an agenda, (3) a study lead, and (4) subject matter experts.
	Team Building	If you have less than 7 people in a study, add SME(s)
Paopla	Team Building	For participant selection, bring a mix of deep experts and "smart but not brainwashed" participants.
reopie	"Disrupters"	For future concept generation, get a participant "X" in the room to generate crazy ideas that get people thinking.
	Team Dynamics	Consider Hanlon's razor.
	Team Building	Bring in new disciplines to the process (e.g. art, design) for a broader paradigm.
	Goals & Final Product	When setting up a study, make sure you have: (1) a clearly defined goal and (2) what the final product will be.
	Research (Background Info)	When looking for a unique contribution area, compare to other conference presentations.
	Benefit	When deciding the type of funding to seek, enumerate the key "benefits" to the funding source.
Pre-Study Processes	Visual Study Flow	For documenting heuristics, mentally walk through a study.
	Agenda	For study planning, start with an agenda from a study that went well, then modify it.
	Research	Try to enter the study with as much background
	(Background	information as possible to start answering the questions
	Info)	and meeting objectives right away
	Template	When prompting people for specific information (ex: the elements of an architecture), consider making some kind of template to guide the conversation.

	Research (Background Info)	Perform background research (past studies, SMEs)	
	Study Size	When an A-Team study gets larger than 15 people, break up study into smaller groups	
	Remote Participants	When running an A-Team study, limit the number of remote participants	
	Parking Lot	When discussions in an A-Team study get too specific, stop it and place the topic on the "parking lot"	
	Explore Trade Space	For enabling new concepts, capture mission risks and resolve in-session if possible	
	Explore Trade Space	When performing CML 3 studies, generate multiple creative mission architecture concepts (e.g. dozens - don't limit to one or two)	
	"Nimble"	Don't limit process flow to approach based on heuristics - need to be spontaneous to change as required during study	
	Incubation	In the middle of an A-Team session, take a pause to make a rough risk assessment (H / M / L) for each element under consideration	
G. 1	Incubation	In the first phase of an A-Team study, allow and encourage solutions that don't adhere to established heuristics	
Study Processes	Challenge Assumption	When using technical heuristics, pause mid-study and ask - what if we rejected (replaced) a central assumption?	
	Study Size	For action/timeline planning, keep the group small; break into sub-groups if needed (≤ 5 people)	
	Document	In an A-Team study, take lots of photos of the study participants (action shots)	
	Breaks	In an A-Team study, take a break every couple of hours	
	Brainstorming	For brainstorming, Action: group stands at board, writes ideas on stickies, places on board	
	Affinity Map	For facilitation, Note: see "De Bono Methods" for huge set of heuristics that we use often	
	Study Size	When working through multiple architectures or ideas quickly, consider breaking the team into groups to tackle different things and then regroup together	
	Parking Lot	When there is a large and/or outspoken group of participants, utilize a "parking lot" to save conversations for later but keep the study moving	
	Simplest Answer	Occam's razor	

	Rabbit Holes	Avoid technical <u>rabbit holes</u> , digitize technical heuristics <u>fight negative</u> heuristics. Avoid arguments
		about technical infeasibility via quick calculation.
	Dominate	Challenge <u>champions</u> , stir up preconceptions, don't
	Personalities	allow a person to champion an idea too hard. Force
		Derive iteration forestale (conserve iteration
	Idea Generation	During Idea generation, freestyle (generate ideas, do not judge) Avoid rabbit holes. Group (get 22)
	Idea Generation	vote. Cull all at once. Move on swiftly.
	Affinity Map	Brainstorming - sorting/binning
	Common	Conversations; Develop novel shared languages and
	Language	meaning
	Trade Space	Sketching (See sense giving, sense making??)
	Trade Space	Circular process (sense giving, sense making??)
	Trade Space	Double Diamond. Look at the trade space, ID the best options, then ID the solutions for that
		When using advanced simulations, make sure the
	Simulations	results match 1st order expectations
		When building up code, check sub segments along the
Tools	S/W Develop	way
10013		When advancing work, lock / save prior versions to not
	"Save"	be edited
	Science Value	For trade studies, use science value metrics to
	Metrics	differentiate and compare mission architectures
	X7' 1	For the study session, provide visuals that transport
	Visuals	people's thought to study context
		For brainstorming, provide visual map of some kind to
	Viguala	organize people's inoughts, have them place sucky
	Food	Before the session get food
Resources	1000	When coming up with new ideas make use of
		drawings or images that you prepare beforehand to
	Visuals	help guide the conversation
	Key Graphics	Keystone graphics - see boundary objects
	Key Graphics	Build models - see boundary objects
	Key Graphics	Boundary objects -first order -second order

APPENDIX E. SURVEY QUESTIONS, STUDY III

- 1. Name:
- 2. Team Number:
- 3. List the design methods or tools (if applicable) used for the first project assignment.
- 4. List your individual duties or tasks.
- 5. How did your team narrow down ideas? Select all that apply.
 - a. Voting process
 - b. Discussion until consensus
 - c. Criteria-based evaluations
 - d. Other (please specify)
- 6. Mark how accurately the following statements describe your role in the decision making so far.
 - a. I advocated for my own ideas.
 - b. I preferred a topic idea presented by a teammate.
 - c. I feel satisfied by the final choice of project topic that my team made.
 - d. My voice was overruled or unheard during selection.
 - e. I disagreed with or disliked one or more project topic ideas of my teammates.
 - f. I would have preferred an idea that was not selected.
 - g. I was or would have been disappointed if my topic was not chosen.
- 7. If your reasoning for decision making was not captured in the previous question, please specify here.
- 8. Please answer the following as accurately as you can.
 - a. How much effort did you expend on generating ideas?
 - b. How much effort did the ream spend on selecting a topic? (Person-hours of group meetings
- 9. Please list your top three ideas from the "Individual Team Project Topic Ideation" assignment, in ranked order.

- 10. How much research was needed for each idea?
- 11. Answer the following regarding research for your first/second/third idea:
 - a. I was able to develop this idea based on personal experience.
 - b. I did not need to search for information to develop this idea.
 - c. Any research performed was made in hopes of confirming this idea as a valid problem.
 - d. Any research performed was made in hopes of rejecting this idea as a problem.
 - e. I researched this idea by identifying current solutions.
 - f. I easily recognized this problem in my own life.
 - g. I liked this idea because of the benefits it can provide.
 - h. I identified this idea because of the negatives of the current solution.
 - i. I was aware of this problem from prior research/design problems I have worked on.
- 12. Choose your preferred idea if you were to consider:
 - a. Design for Sustainability
 - b. High Risk, High Reward
 - c. Payment to do the project
 - d. Personal day-to-day relevance
 - e. Highest potential profitability
 - f. Novelty/uniqueness
 - g. Personal expertise in the area
 - h. More time to complete the design process
 - i. More access to data/end users to inform the design process
 - j. More money to spend on the design process
 - k. Technical Feasibility
 - 1. Manufacturing Feasibility
 - m. Competitive advantage to succeed
 - n. Personal passion towards the topic
- 13. What are your initial thoughts about the market of the problem chosen?
 - a. There is a large market for this product.
 - b. There is a wide variety of end users/stakeholders.
 - c. The market is niche with only a specific set of end users that would be interested in purchasing the product.
 - d. I chose this problem because I am part of this potential market.
 - e. There is high competition in the market for this product.
 - f. The market for this product doesn't exist yet.
 - g. I have purchased products within this market.
- 14. Once this class is over, I plan to pursue development of this product and market launch.
- 15. This product would be a disruptive innovation if introduced to the market.
- 16. Before having performed a customer needs assessment, list up to 5 customer needs that you currently believe will be most important for the design to include.
- 17. What, if any, are the current solution(s) on the market that you are aware of?

18. In no more than 2 sentences, describe your first idea of what the solution will look like.

- 1. Name:
- 2. Team Number:
- 3. Select all the design methods or tools (if applicable) used to develop customer needs.
 - a. Interviews
 - b. Surveys / Questionnaires
 - c. Focus Groups
 - d. Data from other researchers
 - e. Observation
 - f. Ethnography
 - g. Empathic Design
 - h. Lead Users
 - i. Affinity Mapping
 - j. Other (please specify)
- 4. Describe the individual duties or tasks that you performed in support of the development of your team's customer needs.
- 5. How did your team rank the importance of customer needs? Select all that apply.
 - a. Voting process
 - b. Discussion until consensus
 - c. Reliance on customer feedback
 - d. Other (please specify)
- 6. How many stakeholders did your team directly interact with?
- 7. How many stakeholders did YOU directly interact with?
- 8. Indicate your level of agreement with the following statements describing your role in the team decision making for customer needs since the last survey.
 - a. I advocated for my own beliefs.
 - b. I was heavily invested in the customer needs gathering process.
 - c. I feel satisfied by the preliminary customer needs presented by the team.
 - d. I feel satisfied with the logical reasoning for the customer needs presented by teammates.
 - e. I feel satisfied with the importance rankings placed on each need.
 - f. My voice was overruled or unheard when generating the customer needs.
 - g. My voice was overruled or unheard when categorizing the importance of customer needs.
- 9. Mark which time span accurately reflects the following to the best of your knowledge.
 - a. How much effort did you expend on generating customer needs? (Person-hours of individual effort)
 - b. How much effort did the team spend on generating customer needs? (Personhours of group meetings)

- 10. How do you feel about the stakeholders chosen for gathering customer needs?
 - a. They were the most available set of people.
 - b. They may not necessarily be the best depiction of our market.
 - c. They were exactly the users we wanted to target.
 - d. I would have needed more time to collect data from the people I wanted to include.
 - e. I would have needed more resources to collect data from the desired population.
 - f. I was aware that one or more of the subjects had previous knowledge or feelings about the problem.
- 11. If you have any thoughts about your stakeholders that were not captured in the above statements, please share them here:
- 12. How did the customer needs analysis impact your view of the project topic?
 - a. The customer needs analysis confirmed my belief regarding the validity of the problem.
 - b. The customer needs analysis altered my belief regarding the validity of the problem.
 - c. I became aware of new customer needs I did not previously consider.
 - d. The customer needs analysis confirmed the customer needs that I was aware of beforehand.
 - e. The customer needs analysis portrayed some of my initial thoughts for customer needs as not relevant or important.
- 13. Please rank the three customer needs that YOU believe are the most important to the project. Write them in order of importance (Customer Need #1 is the most important, #3 is the third most important).
- 14. Answer the following statements for Customer Need #1/#2/#3:
 - a. I agree with the ranking of this need.
 - b. This need should be easy to satisfy with our design solution.
 - c. We will have the resources to satisfy this need within a potential design solution.
 - d. We have the time to satisfy this need with our design solution.
 - e. This need requires revising the problem statement.
 - f. This need will be easy to ideate solutions for.
 - g. I am the one who identified this customer need.
- 15. List the design methods or tools (if applicable) used to develop target specifications
 - a. Quality Function Deployment (House of Quality)
 - b. Benchmarking
 - c. Functional Decomposition
 - d. Function Structure Diagrams
 - e. Other (please specify)
- 16. Describe the individual duties or tasks that you performed in support of the development of your team's target specifications.
- 17. How did your team agree on the final set of target specifications? Select all that apply.
 - a. Voting process
 - b. Discussion until consensus

- c. Reliance on customer feedback
- d. Other (please specify)
- 18. Indicate your level of agreement with the following statements describing your role in the team decision making for target specifications since the last survey.
 - a. I advocated for my own beliefs.
 - b. I was heavily invested in the development of target specifications.
 - c. I feel satisfied by the preliminary target specifications presented by the team.
 - d. I feel satisfied with the logical reasoning for the target specifications presented by teammates.
 - e. My voice was overruled or unheard when generating the target specifications.
- 19. Mark which time span accurately reflects the following to the best of your knowledge.
 - a. How much effort did you expend on generating target specifications? (Personhours of individual effort)
 - b. How much effort did the team spend on generating target specifications? (Personhours of group meetings)
- 20. Please rank the three target specifications that YOU believe are the most important to the project. Write them in order of importance (Target Specification #1 is the most important, #3 is the third most important).
- 21. Answer the following statements for Target Specification $\frac{1}{\frac{2}{3}}$:
 - a. I agree with the use of this target specification.
 - b. It will be easy for the team to meet this target specification.
 - c. The target specification is a proper target to aim for in this class.
 - d. The specification will definitely meet one or more of the customer's needs.
 - e. The target specification will separate our design solution from competing products.
 - f. This target specification will be easy to ideate solutions for.
 - g. I am the one who identified this target specification.
- 22. After identifying customer needs and target specifications, how do you feel about the market of the problem chosen?
 - a. There is a large market for this product
 - b. There is a wide variety of end users/stakeholders.
 - c. The market is niche, with only a specific set of end users that would be interested in purchasing the product.
 - d. I am part of the potential market for this product.
 - e. There is high competition in the market for this product.
 - f. The market for this product doesn't exist yet.
 - g. I have purchased products within this market.
 - h. Once this class is over, I plan to pursue development of this product and market launch.
 - i. This product would be a disruptive innovation if introduced to the market.
- 23. After identifying customer needs and target specifications, are there any current solution(s) on the market that you are now aware of?

- 24. After identifying customer needs and target specifications, in no more than 2 sentences, describe your current idea of what the solution will look like.
- Survey 3
- 1. Name
- 2. Team Number
- 3. What idea generation methods did you use to develop ideas **individually**? Select all that apply.
 - a. Design by Analogy
 - b. Bio-Inspired Design
 - c. Brainstorming
 - d. SCAMPER
 - e. Morphological Analysis
 - f. Other
- 4. How did you develop ideas as a team? Select all that apply.
 - a. Design by Analogy
 - b. Bio-Inspired Design
 - c. Brainstorming
 - d. SCAMPER
 - e. Morphological Analysis
 - f. Other
- 5. Describe the individual duties or tasks that you performed in support of the team idea generation.
- 6. Mark which time span accurately reflects the following to the best of your knowledge.
 - a. How much effort did you expend on generating ideas individually? (Personhours of individual effort)
 - b. How much effort did the team spend on generating ideas? (Person-hours of group meetings)
- 7. How do you feel about all ideas generated, both individually and as a team?
 - a. I believe my own ideas were the best set generated.
 - b. I feel satisfied by the quality of ideas presented by other members of the team.
 - c. There was a wide variety of ideas generated.
 - d. The ideas produced by the team ideation process were better than the ideas produced by the individual ideation.
 - e. It was difficult to systematically generate ideas for this design problem.
 - f. I was very involved in the team's idea generation session.
 - g. I relied on my past experiences to generate ideas.
 - h. I believe all group members put in the same amount of effort into individual ideation.
 - i. I believe all group members put in the same amount of effort into team ideation.

- j. My ideas were taken seriously as potential concepts to move forward in the project.
- 8. Out of ALL ideas generated, by all team members, please write out what you believe were the best three ideas. Rank them in order from best idea (Idea #1) to third best idea (Idea #3). If you need to refer to your notes or design process documents to answer this question, please do so.
- 9. Answer the following questions for Idea #1/#2/#3:
 - a. I came up with this idea.
 - b. I contributed to generating this idea significantly.
 - c. I had no role in generating this idea.
 - d. It was time consuming to generate this idea.
 - e. It was difficult to generate this idea.
 - f. This idea is similar to how I imagined the solution at the beginning of the project.
 - g. Other team members like this idea as well.
- 10. Out of the ideas you considered to be the best three ideas, choose your preferred idea if you were to consider:
 - a. Design for sustainability
 - b. High risk, high reward
 - c. Payment to do the project
 - d. Personal day-to-day relevance
 - e. Highest potential profitability
 - f. Novelty/uniqueness
 - g. Personal expertise in solution components
 - h. Ability to produce a sketch or CAD prototype of the design
 - i. Meeting the most critical customer needs
 - j. More time to complete the design process
 - k. More access to data / end users to inform the design process
 - 1. More money to spend on the design process
 - m. Technical feasibility
 - n. Manufacturing feasibility
 - o. Competitive advantage to succeed
 - p. Personal passion towards the solution
 - q. Simplest solution that meets the Customer Needs
- 11. How did your team determine which concept to move forward? Select all that apply.
 - a. Pugh Selection Matrix
 - b. QFD Selection Matrix
 - c. Multiple Criteria Decision Making
 - d. Voting Process
 - e. Discussion until consensus
 - f. Other (please specify)
 - g. I wasn't involved in this decision.
- 12. Describe the individual duties or tasks that you performed in support of concept selection.

- 13. Indicate your level of agreement with the following statements describing your role in the team decision making for concept selection since the last survey.
 - a. I advocated for my own beliefs concerning the process for selecting a concept.
 - b. I advocated for my own beliefs concerning which concept should move forward.
 - c. I was heavily invested in the concept selection process.
 - d. I feel satisfied with the logical reasoning presented by teammates for choosing the final concept to move forward.
 - e. I feel satisfied with the criteria used to choose the final concept to move forward.
 - f. My voice was overruled or unheard when choosing the final concept to move forward.
- 14. How much effort did you expend individually on concept selection? (Person-hours of individual effort)
- 15. How much effort did the team spend on concept selection? (Person-hours of group meetings)
- 16. How do you feel about the final concept the team chose to move forward?
 - a. The concept should meet all of our customer needs.
 - b. Developing the concept will be difficult and complicated but worthwhile.
 - c. I would have preferred our concept to be more innovative.
 - d. I would have preferred our concept to be chosen with more awareness of the semester time constraints.
 - e. I would have preferred our concept to be more technically complex.
 - f. I would have preferred our concept to be more technically feasible.
 - g. Overall, I am satisfied with the concept the team chose to move forward.
 - h. I believe we left a much better concept on the table.
 - i. The chosen concept is similar to what I had in mind when beginning the project.
 - j. I would have rather chosen a more challenging concept, even though it may have failed.
- 17. If you have any thoughts about your chosen concept that were not captured in the above statements, please share them here:
- 18. After performing ideation and concept selection, how do you feel about the market of the problem chosen?
 - a. There is a large market for this product.
 - b. There is a wide variety of end users / stakeholders.
 - c. The market is niche, with only a specific set of end users that would be interested in purchasing the product.
 - d. I am part of the potential market.
 - e. There is high competition in the market for this product.
 - f. The market for this product doesn't exist yet.
 - g. I have purchased products within this market.
 - h. Once this class is over, I plan to pursue development of this product and market launch.

- i. This product would be a disruptive innovation if introduced to the market.
- 19. After performing ideation and concept selection, how do you feel about moving into user feedback phase of the design process?
 - a. The concept will be easy to produce a prototype for user feedback.
 - b. Users will likely have more comments than we can accomodate.
 - c. It will be difficult for users to understand the product without a physical, working prototype.
 - d. The end users will be easily accessible for the user feedback portion of the project.
 - e. I believe we will have to change many aspects of our concept before the final concept is presented at the end of the semester.
 - f. The user feedback will likely have a sample size that is smaller than preferred
 - g. The team will lack access to experts that are critical to judging the validity of the design.
 - h. The method for communicating the design concept to users for feedback will not be ideal.
- 20. Are there any assumptions or shortcuts that the team needs to make to receive virtual feedback on the design concept? If so, write them here:
- 21. Do you have any other thoughts about the next phase of the project? If so, write them here:

- 1. Name
- 2. Team Number
- 3. How did your team communicate the design concept(s) to end users? Select all that apply.
 - a. Hand sketch(es)
 - b. CAD based model(s)
 - c. Physical prototype(s)
 - d. Video of concept(s)
 - e. Written description(s)
 - f. Other (please specify)
- 4. How did your team collect user feedback on your design concept(s)? Select all that apply.
 - a. Surveys
 - b. In-person Interviews
 - c. Virtual Interviews
 - d. Focus Groups
 - e. Observations
 - f. Other (please specify)
- 5. How did your team determine refinements to the design concept(s) based on user feedback? Select all that apply.
 - a. Voting process

- b. Discussion until consensus
- c. Criteria-based evaluations
- d. Reliance on the user feedback
- e. Other (please specify)
- 6. Describe the individual duties or tasks that you performed in support of gathering user feedback.
- 7. Describe the individual duties or tasks that you performed to incorporate user feedback into the refinement of your design concept.
- 8. How many end users did your team directly interact with to inform the process for user feedback?
- 9. Please mark which time span accurately reflects the following to the best of your knowledge.
 - a. How much effort did you expend on gathering user feedback? (Person-hours of individual effort)
 - b. How much effort did you expend on refining your design concept(s)? (Personhours of individual effort)
 - c. How much effort did the team spend on gathering user feedback? (Personhours of group meetings)
 - d. How much effort did the team spend on refining your design concept(s)? (Person-hours of group meetings)
- 10. Please indicate your level of agreement with the following statements describing your role in decision making for user feedback since the last survey.
 - a. I was heavily involved in the user feedback gathering process
 - b. I felt convinced by the logical reasoning presented by teammates when discussing feedback.
 - c. My voice was overruled or unheard when discussing the importance or interpretation of the feedback received.
 - d. I advocated for my own beliefs concerning how the design concept(s) should or should not change based on user feedback.
 - e. I was heavily involved in the design concept(s) refinement process.
 - f. I feel satisfied with the refinements made to the design concept(s), incorporating the user feedback.
 - g. I feel satisfied with the logical reasoning for the design concept refinements presented by teammates.
 - h. My voice was overruled or unheard when deciding what refinements would be made to the design concept(s).
- 11. How do you feel about the end users chosen for gathering user feedback?
 - a. They were the most available set of people.
 - b. They may not necessarily be the best depiction of our market.
 - c. They were exactly the users the team wanted to target.
 - d. I would have needed more time to collect data from the people I wanted to include.
 - e. I would have needed more resources to collect data from the desired population.

- f. I was aware that one or more of the subjects had previous knowledge or feelings about the design concept.
- g. The team has personal relationships with the end users providing feedback.
- 12. If you have any thoughts about your end users that were not captured in the above statements, please share them here:
- 13. How do you feel about the process used for gathering user feedback?
 - a. The method(s) for communicating the design to users was able to produce meaningful feedback.
 - b. I am satisfied with the sample size of end users the team was able to obtain.
 - c. I would have preferred a different method of communicating the design concept(s) to the end users.
 - d. The team was able to collect feedback on the design concept(s) without any confusion or vagueness in the responses.
 - e. The process focused on confirming that the design concept(s) meet(s) the customer needs.
 - f. The process focused on receiving suggestions for how to improve the design concept(s).
 - g. The user feedback confirmed my beliefs regarding the design concept as a valid solution for meeting the customer needs.
 - h. The design concept(s) will require major refinements to be valuable to the customer.
- 14. If you have any thoughts about the user feedback process that were not captured in the above statements, please share them here:
- 15. After receiving user feedback, please enter what you believe to be the three most important design decisions made, listed from most important (Decision #1) to third most important (Decision #3). These should be specific decisions concerning whether to modify or not modify aspects of your design, and how the design was modified, based on the user feedback received.
- 16. Please answer the following questions for Decision #1/#2/#3:
 - a. I agree with this decision.
 - b. I am the one who recommended this decision.
 - c. This was based on positive feedback about the design concept(s).
 - d. This decision led to design concept(s) refinements.
 - e. The decision was based on feedback that altered my beliefs about the design concept(s).
 - f. The decision focused on aspects of the design concept(s) that I was heavily involved in during earlier stages of the project.
 - g. The team has adequate information to justify this decision made in response to the user feedback.
 - h. We invested a significant amount of time and effort into this aspect of the design concept(s) before user feedback.
- 17. After receiving user feedback and performing design refinements, how do you feel about the market of the problem chosen?
 - a. There is a large market for this product.

- b. There is a wide variety of end users / stakeholders.
- c. The market is niche, with only a specific set of end users that would be interested in purchasing the product.
- d. I am part of the potential market.
- e. There is high competition in the market for this product.
- f. The market for this product doesn't exist yet.
- g. I have purchased products within this market.
- h. Once this class is over, I plan to pursue development of this product and market launch.
- i. This product would be a disruptive innovation if introduced to the market.
- 18. Do you have any other thoughts about the project moving forward? If so, please describe them here:

- 1. Name
- 2. Team Number
- 3. What methods did your team use to carry out your economic analysis? Select all that apply.
 - a. Net Present Value
 - b. Break-Even Analysis
 - c. Base Case Model
 - d. Sensitivity Analysis
 - e. Other (please specify)
- 4. Describe the individual duties or tasks that you performed in support of developing your economic analysis.
- 5. Please mark which time span accurately reflects the following to the best of your knowledge.
 - a. How much effort did you expend on performing an economic analysis? (Person-hours of individual effort)
 - b. How much effort did the team spend on performing an economic analysis? (Person-hours of group meetings)
- 6. Indicate your level of agreement with the following statements describing your role in the team decision making for the economic analysis.
 - a. I advocated for my own beliefs concerning the criteria for the economic analysis.
 - b. I was heavily invested in the economic analysis.
 - c. I feel satisfied by the details of the analysis presented by the team.
 - d. I feel satisfied by the logical reasoning presented by teammates for interpreting the results.
 - e. My voice was overruled or unheard when performing our economic analysis.
- 7. How do you feel about the economic analysis performed by the team?
 - a. The economic analysis suggests the final design must be improved for profitability.

- b. The analysis confirmed my beliefs about the strength of the final design to be profitable.
- c. The economic analysis would have indicated higher profits if the team had more access to critical information and resources.
- d. The economic analysis excluded some factors that may have led to the conclusion that our final design would not be profitable.
- 8. If you have any thoughts about the economic analysis that were not captured in the above statements, please share them here:
- 9. How do you feel about your final design?
 - a. Overall, I am satisfied with the final design.
 - b. This final design is similar to how I imagined it at the beginning of the project.
 - c. Many aspects of the final design were my own ideas.
 - d. The final design was difficult to develop.
 - e. I believe we left a much better design alternative on the table.
 - f. Developing the final design was worthwhile.
 - g. I would have preferred to change to a different design if more time was available.
 - h. My beliefs were confirmed regarding the feasibility of the final design.
 - i. This design could be realistically profitable.
- 10. If you have any thoughts about your final design chosen that were not captured in the above statements, please share them here:
- 11. In 2-3 sentences, describe one major decision about the design or design process that you would change if you could do the project over again. Why did you/your team make this decision? Were you influential in making this decision? What would you have done differently?
- 12. In 2-3 sentences, describe one major decision about the design or design process that you believe was critical to your design success. **Why** did you/your team make this decision? **Were you influential** in making this decision?
- 13. In 2-3 sentences, describe any issues you encountered in your design process during the semester. This can be any difficulties that required you to adjust or reassess the direction of your design. **Do you believe** you should have seen this/these issues coming beforehand? **Why** or why not?
- 14. Looking back on the decisions made during the semester, is there anything else you would have done differently?
 - a. I would have preferred a different problem space.
 - b. I would have revised our method for generating customer needs.
 - c. I would have placed emphasis on different customer needs.
 - d. I would have given our team more realistically attainable design specifications.
 - e. I would have given myself more time to ideate.
 - f. I would have preferred a different concept for the final design.
 - g. I would have voiced my opinion more about critical decisions I disagreed with.

- h. I would have made more modifications to the design after the user feedback.
- i. I would have taken more risks to make the final design more innovative.
- 15. Do you have any other thoughts about how the project developed over the semester? If so, please share them here:
- 16. After performing an economic analysis, how do you feel about the market of the final design chosen?
 - a. There is a large market for the final design.
 - b. There is a wide variety of end users / stakeholders.
 - c. The market is niche, with only a specific set of end users that would be interested in purchasing the final design.
 - d. I am part of the potential market.
 - e. There is high competition in the market for the final design.
 - f. The market for the final design doesn't exist yet.
 - g. I have purchased products within this market.
 - h. Once this class is over, I plan to pursue development of the final design and market launch.
 - i. The final design would be a disruptive innovation if introduced to the market.
- 17. What is your age group?
- 18. What is your gender?
- 19. How would you classify yourself? Select all that apply.
- 20. Please list the degree(s) you are currently pursuing, and how far along you are in the degree program(s). For example: Ph.D. in Mechanical Engineering, 2nd Year.
- 21. What is your first language? Other languages spoken?
- 22. When did you start working/studying as a designer?
- 23. Please describe any design-related internships or jobs you've held, including dates/duration:
- 24. Please respond to the following statements about yourself as honestly as possible.
 - a. I am comfortable sketching my ideas.
 - b. I am a creative person.
 - c. If I have spent more time on an idea or project, I am more reluctant to abandon it.
 - d. If I am the owner of an idea, I am more inclined to want to pursue that idea on a design team.
 - e. If I have a hypothesis, I hope it will be confirmed by the data I collect.
 - f. Usually, the solution that exists to a design problem (the status quo) is a good one.
 - g. When I write interview or survey questions for user feedback, I am careful to consider positive or negative wording.
 - h. When I'm tired or stressed, I think I make different design decisions than I would make otherwise.
- 25. When I don't have a large enough sample size, I base my design decisions on:

APPENDIX F. JOURNAL QUESTIONS, STUDY IV

Design Journal #1 - Generalized Design Process.

1. Based on the machine which you have spent the most time using in the past year, please list the machine for which you are participating in this study.

Think back on your time interacting with this machine. Based on your experiences, please fill out the following information:

- 2. List what you believe to be the 5-10 most important parameters and settings when using this machine.
- 3. Document any planning processes/strategies/actions that you typically go through before using this machine. Please be as thorough as possible.
- 4. Document the processes/strategies/actions that you believe that you typically follow while using this machine. Please be as thorough as possible.
- 5. In reference to Questions 3-4, are there any instances where you would <u>not</u> adhere to these processes/strategies/actions? Describe those contexts. What processes/strategies/actions would be taken instead?
- 6. Document the most common types of troubleshooting that you believe you have encountered with this machine. How do you become aware of these failures, and how do you manage to avoid them in future builds?
- 7. List your 5-10 most important lessons learned through your use of this machine. If you were going to teach someone else how to have the highest likelihood of success with this machine to produce high quality parts, what would you share with them?
- 8. List your most common rules of thumb that you apply to your designs when designing parts for fabrication on this machine.
- 9. Describe how you determine if your part has been built successfully. What are the things you look for when determining quality?

10. If you are familiar with other additive or subtractive manufacturing machines, list any rules of thumb that you have tried to transfer to this machine from your experience with other machines. How successful were these in producing high quality parts? If you are not familiar with other manufacturing machines, you may skip this question.

Design Journal #2 - Most Recent Design Experience.

Think about the last part that you had to build. For that manufacturing session, please fill out the following information:

- 1. What was the overall objective for building this part?
- 2. What was the material being used for this build?
- 3. What were the rough dimensions of the part?
- 4. Describe the geometry of the part, or provide a sketch of it here.
- 5. List the key machine parameters and settings, and the corresponding values used for manufacturing this part. If you cannot recall these values, you may skip this question.
- 6. Were there any differences in strategies used to plan this task compared to the generalized steps of Journal #1? If so, describe those differences here.
- 7. Were there any differences in strategies used to perform this task compared to the generalized steps of Journal #1? If so, describe those differences here.
- 8. List and describe any troubleshooting you performed to improve the build while it was underway, if applicable.
- 9. Describe the results of the build session. How did the part turn out? What went well and what went poorly, and why? Use sketching or images to describe any problems that arose in the build, if needed.
- 10. Describe any insights derived from the outcomes of this build that may impact future builds.

APPENDIX G. INTERVIEW QUESTIONS, STUDY IV

The purpose of this study is to understand and describe how users of various advanced manufacturing machines perceive the processes and strategies they use as they become more experienced with these machines. More specifically, with these design journals and interviews we hope to identify some of the current heuristics being employed before and during the use of these machines to produce high quality designs. A formal definition of a heuristic is provided below:

Heuristic: A context-dependent directive, based on intuition, tacit knowledge, or experiential understanding, which provides design process direction to increase the chance of reaching a satisfactory but not necessarily optimal solution.

Informally, heuristics are often referred to as "rules of thumb." One can think of a heuristic as a combination of a context in which the heuristic is applicable, and a corresponding action to be considered. A heuristic may then have the following form: "When in this kind of situation, consider this action."

Based on this understanding of heuristics, and the information you provided in your design journals, I have attempted to put your design process into this heuristic format.

I noticed (insert "context-action" heuristic) in your process from your design journal.

- 1. Is this an accurate depiction of how you perceive this part of your design process?
 - a. If not, then why not?
- 2. Walk me through your rationale for choosing this heuristic.
 - a. How would you describe the reliability of this heuristic?
 - b. How often do you use this heuristic in your process?
- 3. Walk me through how you developed this heuristic.
 - a. How did this heuristic evolve? Is it constant or still changing over time?
- 4. Are there any other alternative actions you could have taken?

- a. If so, did you consider them here?
- b. Have you used those before? In what contexts?
- c. Why did you choose this heuristic over the alternatives?
- 5. What are some of the key criteria you consider when choosing to use this heuristic?
- 6. Is there another aspect of the heuristic or sequence of heuristics that I am not seeing?
 - a. If so, please explain.

(repeat process for all heuristics from journal)

Now, I want to ask some clarifying questions regarding the details you provided for troubleshooting and lessons learned on this machine.

Lastly, I want to discuss your process in more general terms.

- 1. Did any of your experiences with other machines or builds lead to your methods on this machine? How well do processes from other machines translate?
- 2. Do you typically document any of the knowledge discussed today?
 - a. If so, how do you do that?
 - b. What are the issues you find with maintaining that knowledge documentation?
- 3. What aspects of your manufacturing process do you wish you had more intuition or strategies for? How are you currently planning to obtain this?
- 4. How does knowledge from team members/advisors/supervisors impact your process development?
 - a. How do you know you can trust these heuristics from others before you try using them yourself?
- 5. How does knowledge from textbooks or classroom education impact your process development?
- 6. How do standards in research, in industry, or from machine manufacturers impact your process development?

APPENDIX H. SET OF HEURISTICS, STUDY IV

ID	Heuristic
P1.1	If the part can be easily machined through simple or no modifications, do not print the part.
P1.2	After loading powder into the machine hopper, tamp and level the powder to
	ensure a uniform spread layer.
P1.3	When loading powder into the hopper, load large quantities and only sieve when
	necessary.
P1.4	If a post-build heat treatment is necessary, consider overbuilding with machining
	allowances to account for the treatment contaminating surface layers.
P1.5	When generating supports, first determine the build removal method, such as
	EDM, band saw, or manual removal.
P1.6	When preparing the build layout, avoid recoater jams by orienting components such that they do not have edges parallel to the recoater blade.
P1.7	When orienting surfaces, keep surface texture requirements in mind.
P1.8	When orienting build to machine axis, consider how orientation interacts with
	process strengths/weaknesses such as pore size and fatigue life.
P1.9	When developing supports, use solid supports if possible to avoid the costs and
D1 10	risks devoted to designing a complex support.
P1.10	To avoid difficulty with leveling build plate/dialing in first layer thickness,
	machine build plates to be flatter so that the first powder layer thickness is
D1 11	When dialing in the first layer thickness do not be everly concerned with
F 1.11	precision, as the first layer will not be included in your final part.
P1.12	If a component needs high fatigue resistance, consider the build area density, gas
	flow, and recoat directions to avoid splatter/large particles that might negatively
	impact part quality.
P1.13	If you have a delicate build involving a lot of thermal distortion, consider using
	a 'soft' recoater brush.
P1.14	If the recoater blade crashes, consider increasing your layer size to decrease the
	chances of another crash.
P1.15	If the recoater blade crashes, consider changing the recoater blade type.
P1.16	To determine part quality, use a measurement process to check for irregular
	surface textures indicating poor build quality.
P1.17	To determine part quality, visually check for colors that may indicate too much
	heat or lack of heat sinking.
P2.1	Before building your part, first consider how print orientation, feature size, and
	part size will influence your build.
P2.2	To avoid thermal warpage, use support structures as a heat sink.
P2.3	If overhangs are present in your design, first try to reorient the part for printing.

P2.4	If overhangs are present and the design cannot be reoriented, try using support
	structures.
P2.5	If overhangs are present and you cannot use supports or reorient your design,
	modify the design to remove the overhangs.
P2.6	If a feature size is too small, increase its size to avoid overbuilding.
P2.7	To prevent collisions from thermal warpage, increase your layer size.
P2.8	To prevent collisions from thermal warpage, use a brush recoater.
P2.9	When setting the build order, build from bottom left to top right to minimize the impact of metal condensate.
P2.10	If you are using recycled powder, it must first be sieved to eliminate large powders that might lead to porosity.
P2.11	When filling the machine with powder, have the powder level at least 2.5 times the height of the bounding box of the build in the hopper.
P2.12	When preparing your part, avoid features requiring high tolerances which would be better served through machining.
P2.13	To account for poor-surface roughness in designs, consider reorientation, modification of design or post-processing methods
P2.14	To assess part quality through dimensional accuracy, use CMM technology.
P2.15	To assess part quality through internal pore detection, use CT technology.
P3.1	When developing the build layout, determine orientation before the use of
	supports, as orientation is more critical for part functionality.
P3.2	When determining build orientation, consider build failures due to thermal warpage or the surface angle to the build direction.
P3.3	If multiple orientations are possible, decide orientation by evaluating part requirements such as surface quality.
P3.4	If you have non-self-supporting features such as overhangs at less than a 45° to the build plane, use support structures
P3.5	If your goal is to reduce residual stress, use a support structure to avoid warping
	and to keep the part physically attached to the plate.
P3.6	When using supports, choose the support type based on your method for
	removal: solid supports for EDM removal, and support structures for band saw removal.
P3.7	If your part is simple enough to be obtained through machining or another
	process, avoid unnecessary costs and do not print the part.
P3.8	For a typical build with a 20 Micron layer height, use the standard parameter sets for the EOS M280.
P3.9	When setting the build order, avoid part contamination by building from the
	lower left to the top right.
P3.10	When part quality is more important, place the part closer to the build plate
	center for higher accuracy.
P3.11	When sieving or adding new powder to the machine, have a second person
	vacuum to mitigate powder plumes, which may cause contamination.
P3.12	When the powder is at a sufficient level, the powder must be then
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	tamped/compacted to remove air pockets.
P3.13	To assess quality through point comparison relative to other parts or processes,
	use CT technology.
P3.14	To assess quality through dimensional accuracy, use CMM technology.
P3.15	To assess quality through characterizing the surface texture, use surface
	metrology.
P3.16	If the amount of powder is double the height of the planned build, no powder
	change is needed.
P3.17	If the amount of powder is not double the build height, and there is powder in
	the collector, sieve the powder and add it to the hopper.
P4.1	Before running the machine, ensure the powder hopper has spreader/suction
	units aligned with the rotating disk, as this is critical for flow rate.
P4.2	At the beginning of your build, wait 20-30 seconds before depositing material
	so the powder has time to reach a consistent flowrate.
P4.3	To obtain the preferred powder quality, keep the powder hopper temperature at
	or above 60 degrees Celsius overnight before the build.
P4.4	If there is a powder hopper malfunction, reset the additive head back to its
	original position, then re-run the code.
P4.5	If a powder hopper malfunction continues after being reset, disassemble the
	hopper unit and re-align the spreader/suction and rotating disk.
P4.6	If a powder hopper malfunction continues after the reset and re-alignment, check
	the tubing.
P4.7	If a powder hopper malfunction continues after the reset and re-alignment, and
	tubing has been checked, then try heating the powder up at 90 degrees Celsius
D 4.0	for 24 hours.
P4.8	It a powder hopper malfunction continues after all known troublehshooting steps
D4.0	have been taken, change the powder.
P4.9	when performing the dry run, avoid going full speed so that you can visually
D4 10	Confirm the spots being nit.
P4.10	when performing the dry run, increase the length of your dry run as your build
D4 11	When using a new material start with simple geometries to become familiar
P4.11	when using a new material, start with simple geometries to become familiar
D4 12	When selecting a substrate, consider that nerrow substrates are able to take less
F4.12	energy and heat compared to wider substrates
D/ 12	When propering your build, consider that a perrow substrate produces thicker
F4.15	heads than wider substrates
Ρ / 1/	To assess build quality visually inspect the surface for the preferred abroma or
1 4.14	shiny silver color, rather than colors such as vellow/blue/black/red
P4 15	To assess build quality visually inspect the surface geometry for an even surface
17.13	finish with no dents or visible defects

P4.16	To assess build quality, visually inspect the substrate for no deformation such as
	warping, bending, or excessive melting.
P5.1	Before using the Mazak machine, the first step is to set up a work coordinate
	system of the substrate to align your tool heads.
P5.2	When selecting the work piece, choose the substrate material based on the
	material being used for printing.
P5.3	After setting up a work coordinate system of the substrate, load the g-code
	program.
P5.4	Before building, perform a dry run to verify the work offset and post processor,
	which will catch major errors that might damage the machine.
P5.5	To ensure there is no moisture in the powder that may lead to clumping, keep
	the powder heated for at least half a day before building.
P5.6	After inspecting the powder level, gas flow and powder flow, the machine is
D5 7	ready for use.
P5.7	While the machine is in use, visually inspect intermittently if the laser nozzle is
D5 0	not too nign or too low.
P5.8	when building a part, use bead to bead spacing (also known as overlap/stepover)
D5 0	When setting the layer height of the bade, use an average of the first few layers
13.9	to account for height differences
P5 10	To check the laser nozzle position, visually inspect the brightness level of the
1 5.10	laser
P5.11	If the material is over/under building, slow down/speed up the feed.
P5.11 P5.12	If the material is over/under building, slow down/speed up the feed. If the material is over/under building, change the work offset.
P5.11 P5.12 P5.13	If the material is over/under building, slow down/speed up the feed. If the material is over/under building, change the work offset. If the material is over/under building, and large unevenness of height occurs in
P5.11 P5.12 P5.13	If the material is over/under building, slow down/speed up the feed. If the material is over/under building, change the work offset. If the material is over/under building, and large unevenness of height occurs in the build, Machine a few layers, then print afterwards.
P5.11 P5.12 P5.13 P5.14	If the material is over/under building, slow down/speed up the feed. If the material is over/under building, change the work offset. If the material is over/under building, and large unevenness of height occurs in the build, Machine a few layers, then print afterwards. To determine part quality, look for smooth and homogeneous beads on the top
P5.11 P5.12 P5.13 P5.14	If the material is over/under building, slow down/speed up the feed. If the material is over/under building, change the work offset. If the material is over/under building, and large unevenness of height occurs in the build, Machine a few layers, then print afterwards. To determine part quality, look for smooth and homogeneous beads on the top and side surfaces.
P5.11 P5.12 P5.13 P5.14 P5.15	If the material is over/under building, slow down/speed up the feed. If the material is over/under building, change the work offset. If the material is over/under building, and large unevenness of height occurs in the build, Machine a few layers, then print afterwards. To determine part quality, look for smooth and homogeneous beads on the top and side surfaces. To determine design quality, check the color of the build for dark burn marks or
P5.11 P5.12 P5.13 P5.14 P5.15	If the material is over/under building, slow down/speed up the feed. If the material is over/under building, change the work offset. If the material is over/under building, and large unevenness of height occurs in the build, Machine a few layers, then print afterwards. To determine part quality, look for smooth and homogeneous beads on the top and side surfaces. To determine design quality, check the color of the build for dark burn marks or a rainbow-like color, which can indicate weakened material properties.
P5.11 P5.12 P5.13 P5.14 P5.15 P6.1	If the material is over/under building, slow down/speed up the feed. If the material is over/under building, change the work offset. If the material is over/under building, and large unevenness of height occurs in the build, Machine a few layers, then print afterwards. To determine part quality, look for smooth and homogeneous beads on the top and side surfaces. To determine design quality, check the color of the build for dark burn marks or a rainbow-like color, which can indicate weakened material properties. When developing your CAD model, use the native CAD package for ease of
P5.11 P5.12 P5.13 P5.14 P5.15 P6.1	If the material is over/under building, slow down/speed up the feed. If the material is over/under building, change the work offset. If the material is over/under building, and large unevenness of height occurs in the build, Machine a few layers, then print afterwards. To determine part quality, look for smooth and homogeneous beads on the top and side surfaces. To determine design quality, check the color of the build for dark burn marks or a rainbow-like color, which can indicate weakened material properties. When developing your CAD model, use the native CAD package for ease of editing and to avoid data loss through importing the model.
P5.11 P5.12 P5.13 P5.14 P5.15 P6.1 P6.2	If the material is over/under building, slow down/speed up the feed. If the material is over/under building, change the work offset. If the material is over/under building, and large unevenness of height occurs in the build, Machine a few layers, then print afterwards. To determine part quality, look for smooth and homogeneous beads on the top and side surfaces. To determine design quality, check the color of the build for dark burn marks or a rainbow-like color, which can indicate weakened material properties. When developing your CAD model, use the native CAD package for ease of editing and to avoid data loss through importing the model. When working with simple geometries, use Fusion to develop the CAD model
P5.11 P5.12 P5.13 P5.14 P5.15 P6.1 P6.2	If the material is over/under building, slow down/speed up the feed. If the material is over/under building, change the work offset. If the material is over/under building, and large unevenness of height occurs in the build, Machine a few layers, then print afterwards. To determine part quality, look for smooth and homogeneous beads on the top and side surfaces. To determine design quality, check the color of the build for dark burn marks or a rainbow-like color, which can indicate weakened material properties. When developing your CAD model, use the native CAD package for ease of editing and to avoid data loss through importing the model. When working with simple geometries, use Fusion to develop the CAD model quicker/easier.
P5.11 P5.12 P5.13 P5.14 P5.15 P6.1 P6.2 P6.3	If the material is over/under building, slow down/speed up the feed. If the material is over/under building, change the work offset. If the material is over/under building, and large unevenness of height occurs in the build, Machine a few layers, then print afterwards. To determine part quality, look for smooth and homogeneous beads on the top and side surfaces. To determine design quality, check the color of the build for dark burn marks or a rainbow-like color, which can indicate weakened material properties. When developing your CAD model, use the native CAD package for ease of editing and to avoid data loss through importing the model. When working with simple geometries, use Fusion to develop the CAD model quicker/easier.
P5.11 P5.12 P5.13 P5.14 P5.15 P6.1 P6.2 P6.3	If the material is over/under building, slow down/speed up the feed. If the material is over/under building, change the work offset. If the material is over/under building, and large unevenness of height occurs in the build, Machine a few layers, then print afterwards. To determine part quality, look for smooth and homogeneous beads on the top and side surfaces. To determine design quality, check the color of the build for dark burn marks or a rainbow-like color, which can indicate weakened material properties. When developing your CAD model, use the native CAD package for ease of editing and to avoid data loss through importing the model. When working with simple geometries, use Fusion to develop the CAD model quicker/easier.
P5.11 P5.12 P5.13 P5.14 P5.15 P6.1 P6.3 P6.4	If the material is over/under building, slow down/speed up the feed. If the material is over/under building, change the work offset. If the material is over/under building, and large unevenness of height occurs in the build, Machine a few layers, then print afterwards. To determine part quality, look for smooth and homogeneous beads on the top and side surfaces. To determine design quality, check the color of the build for dark burn marks or a rainbow-like color, which can indicate weakened material properties. When developing your CAD model, use the native CAD package for ease of editing and to avoid data loss through importing the model. When working with simple geometries, use Fusion to develop the CAD model quicker/easier. When working with complex geometries, use Hyper Mill for a more robust CAD model development. If performing multi-axis deposition for complexities such as overhangs, consider
P5.11 P5.12 P5.13 P5.14 P5.15 P6.1 P6.2 P6.3 P6.4	If the material is over/under building, slow down/speed up the feed. If the material is over/under building, change the work offset. If the material is over/under building, and large unevenness of height occurs in the build, Machine a few layers, then print afterwards. To determine part quality, look for smooth and homogeneous beads on the top and side surfaces. To determine design quality, check the color of the build for dark burn marks or a rainbow-like color, which can indicate weakened material properties. When developing your CAD model, use the native CAD package for ease of editing and to avoid data loss through importing the model. When working with simple geometries, use Fusion to develop the CAD model quicker/easier. When working with complex geometries, use Hyper Mill for a more robust CAD model development. If performing multi-axis deposition for complexities such as overhangs, consider increasing the stock size to account for less material utilization (less efficiency).
P5.11 P5.12 P5.13 P5.14 P5.15 P6.1 P6.2 P6.3 P6.4 P6.5	If the material is over/under building, slow down/speed up the feed. If the material is over/under building, change the work offset. If the material is over/under building, and large unevenness of height occurs in the build, Machine a few layers, then print afterwards. To determine part quality, look for smooth and homogeneous beads on the top and side surfaces. To determine design quality, check the color of the build for dark burn marks or a rainbow-like color, which can indicate weakened material properties. When developing your CAD model, use the native CAD package for ease of editing and to avoid data loss through importing the model. When working with simple geometries, use Fusion to develop the CAD model quicker/easier. When working with complex geometries, use Hyper Mill for a more robust CAD model development. If performing multi-axis deposition for complexities such as overhangs, consider increasing the stock size to account for less material utilization (less efficiency). To mitigate large overhangs, consider printing a vertical wall, then machining
P5.11 P5.12 P5.13 P5.14 P5.15 P6.1 P6.2 P6.3 P6.4 P6.5	If the material is over/under building, slow down/speed up the feed. If the material is over/under building, change the work offset. If the material is over/under building, and large unevenness of height occurs in the build, Machine a few layers, then print afterwards. To determine part quality, look for smooth and homogeneous beads on the top and side surfaces. To determine design quality, check the color of the build for dark burn marks or a rainbow-like color, which can indicate weakened material properties. When developing your CAD model, use the native CAD package for ease of editing and to avoid data loss through importing the model. When working with simple geometries, use Fusion to develop the CAD model quicker/easier. When working with complex geometries, use Hyper Mill for a more robust CAD model development. If performing multi-axis deposition for complexities such as overhangs, consider increasing the stock size to account for less material utilization (less efficiency). To mitigate large overhangs, consider printing a vertical wall, then machining away the extra material.
P5.11 P5.12 P5.13 P5.14 P5.15 P6.1 P6.2 P6.3 P6.4 P6.5 P6.6	If the material is over/under building, slow down/speed up the feed. If the material is over/under building, change the work offset. If the material is over/under building, and large unevenness of height occurs in the build, Machine a few layers, then print afterwards. To determine part quality, look for smooth and homogeneous beads on the top and side surfaces. To determine design quality, check the color of the build for dark burn marks or a rainbow-like color, which can indicate weakened material properties. When developing your CAD model, use the native CAD package for ease of editing and to avoid data loss through importing the model. When working with simple geometries, use Fusion to develop the CAD model quicker/easier. When working with complex geometries, use Hyper Mill for a more robust CAD model development. If performing multi-axis deposition for complexities such as overhangs, consider increasing the stock size to account for less material utilization (less efficiency). To mitigate large overhangs, consider printing a vertical wall, then machining away the extra material.
P5.11 P5.12 P5.13 P5.14 P5.15 P6.1 P6.2 P6.3 P6.4 P6.5 P6.6 P6.7	If the material is over/under building, slow down/speed up the feed. If the material is over/under building, change the work offset. If the material is over/under building, and large unevenness of height occurs in the build, Machine a few layers, then print afterwards. To determine part quality, look for smooth and homogeneous beads on the top and side surfaces. To determine design quality, check the color of the build for dark burn marks or a rainbow-like color, which can indicate weakened material properties. When developing your CAD model, use the native CAD package for ease of editing and to avoid data loss through importing the model. When working with simple geometries, use Fusion to develop the CAD model quicker/easier. When working with complex geometries, use Hyper Mill for a more robust CAD model development. If performing multi-axis deposition for complexities such as overhangs, consider increasing the stock size to account for less material utilization (less efficiency). To mitigate large overhangs, consider printing a vertical wall, then machining away the extra material. To mitigate large overhangs, consider multi-axis rotation to produce the part. When your part requires holes, consider printing the component solid, then

P6.8	If you have a large part size, use rotations due to the dimensional limitations of
	the machine.
P6.9	When defining process parameters, keep parameters constant and only change
	one at a time as needed.
P6.10	When defining laser power, use a higher heat input for thin parts and lower heat
	input for dense parts.
P6.11	When defining laser power, use a higher heat input for the first layer and lower
	heat input for each consecutive layer.
P6.12	For metal wire additive, mirror each layer to avoid starting in the same position,
	which compounds deformities in the same location.
P6.13	When deciding the dry run duration, consider how long both the system and
	programming have been in use.
P6.14	For additive processes, to determine a successful build, check for sparking and
	excess wire during the build.
P6.15	For additive processes, to determine a successful build, check for surface
	smoothness and oxidation on the completed part.
P6.16	For machining processes, to determine build quality, check for porosity, as well
	as surface smoothness which can indicate being underbuilt.
P6.17	For machining processes, to determine build quality, check for excess tool wear
2	and if there was chattering during machining.
P7.1	Before starting your build, calibrate the initial work offsets using g-code rather
D7.0	than manually.
P7.2	Before starting your build, make sure the substrate is free of any oxides.
P7.3	Before starting your build, step through the first g-code commands to ensure
	work offsets are correct, which may prevent collisions.
P7.4	If you have not ran the program a few times before, perform a dry run and step
	through the program with the laser off.
P7.5	Once the build begins, observe the first few passes, then rely on auditory cues to
D7 (determine if there are build issues that require inspection.
P7.6	When switching from additive to subtractive operations (or vice versa), measure
D7 7	the deposited/machined surface to determine if any g-code edits are required.
Ρ/./	When switching from additive to subtractive operations (or vice versa), be
D7.0	extremely conscious of your additive and subtractive work offsets.
P/.8	If troubleshooting needs to take place, first check the opinion of a more
D7 0	Experienced user.
F /.9	areasy CNC movement, foodstool, foodrate, or treatment
D7 10	If the design has peresity issues, tune your process parameters in the payt build
F /.10	T in the design has porosity issues, tune your process parameters in the next build.
P/.11	10 determine design success from a metallurgical perspective, use
D7 10	nondestructive testing like U1 to detect pores.
P/.12	10 determine design success, look for your desired surface finishes and
	geometry within a certain degree of uncertainty.

P7.13	When designing your part for the Mazak, limit your design to the capabilities of
	the machine, such as its dimensions and toolpath strategies.
P8.1	When printing simple shapes such as a circle, generate G code by hand or
	MATLAB, rather than programs such as HyperMill or Fusion, to avoid
	limitations of their toolpath generation.
P8.2	When developing G code, set print paths based on where overbuilding may
	occur, such as in corners or other intersecting bead areas.
P8.3	Before running the machine, perform a dry run of the print path to verify the
	print path and detect work object errors or other G code typos that might lead to
	crashes.
P8.4	If machining a printed part, re-probe the work object to account for the printing
	and machining heads being offset.
P8.5	To prevent powder flow failures, ensure dry powder by keeping the heaters on
	the hopper, and give humid hoppers a full day to dry out before building.
P8.6	When using G461 to probe a work offset, do so while the print tool is in the
	spindle, and before inserting the machine head, to prevent a reset of the tool
	length.
P8.7	If machining a printed part, probe the printed part several times in different spots,
	then average the values for a more accurate measurement.
P8.8	For better part quality, run the nozzle closer to the part.
P8.9	If the running the nozzle close to the part, monitor the build carefully to prevent
	crashes.
P8.10	If overhangs are required on your part, use 5-axis positions.
P8.11	To prevent overbuilding, plan to swap directions as much as possible, such as
	reversing the direction for each layer.
P8.12	To ensure bead fusion, design features to have a thickness of at least 1.2mm.
P8.13	When building thin/small features, add pauses between layers to prevent
	overheating, and use the laser power value to determine the delay length.
P8.14	To determine design success, look for a quiet build, smooth surface finish, and
	uniform color throughout the part.
P8.15	If the build makes noise due to significant overbuilding, manually slow down
	the feed rate and deposit more material in lower areas to even out the part.
P8.16	When inspecting the finished product, check for an equal or wider bead width at
	the bottom of the build to show proper fusion, and a flat surface at the top of the
	build.

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