Kenton B. Fillingim
School of Mechanical Engineering,
Georgia Institute of Technology,
Atlanta, GA 30332
e-mail: blane.fillingim@gatech.edu

Richard O. Nwaeri
School of Mechanical Engineering,
Georgia Institute of Technology,
Atlanta, GA 30332
e-mail: ossie@gatech.edu

Felipe Borja
Department of Engineering,
Harvey Mudd College,
Claremont, CA 91711
e-mail: fborja@g.hmc.edu

Katherine Fu
Assistant Professor
School of Mechanical Engineering,
Georgia Institute of Technology,
Atlanta, GA 30332
e-mail: katherine.fu@me.gatech.edu

Christiaan J. J. Paredis
Professor and BMW Chair in Systems Integration
Department of Automotive Engineering,
Clemson University,
Greenville, SC 29607
e-mail: paredis@clemson.edu

Design Heuristics: Extraction and Classification Methods With Jet Propulsion Laboratory's Architecture Team

This study offers insight into the processes of expert designers at the Jet Propulsion Laboratory (JPL) and how they use heuristics in the design process. A methodology for the extraction, classification, and characterization of heuristics is presented. Ten expert participants were interviewed to identify design heuristics used during early stage space mission design at JPL. In total, 101 heuristics were obtained, classified, and characterized. The use of interviews to extract heuristics allowed for researchers to confirm that those heuristics were indeed used by designers. Through the use of post-interview surveys, participants characterized heuristics based on attributes including source/origin, applicability based on concept maturity, frequency of use, reliability, and tendency to evolve. These findings are presented, and statistically significant correlations were found between the participant perceptions of frequency of use, reliability, and evolution 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. Survey results and analysis aim to identify valid attributes for assessing the applicability and value of multiple heuristics for design practice in early space mission formulation.
[DOI: 10.1115/1.4044160]

Keywords: design methodology, design process, design theory and methodology

1 Introduction

Heuristics are rules of thumb providing guidance for choosing the next design action, 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 can 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.

We envision these benefits starting with a repository of heuristics. 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. Documentation must also allow for updating heuristics and attributes as they evolve over time. Overall, we hope to understand if and how the use of heuristics can be described and justified using a normative perspective. In this paper, a step is taken toward obtaining heuristics and determining critical attributes. Interviews and surveys are used to extract and characterize design heuristics used by members of NASA's Jet Propulsion Laboratory (JPL). Specifically, we interviewed ten participants from an early stage mission design group at JPL known as the Architecture Team (A-Team). The focus of this paper 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 does not 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 repeatedly 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

Contributed by the Design Theory and Methodology Committee of ASME for publication in the JOURNAL OF MECHANICAL DESIGN. Manuscript received May 20, 2019; final manuscript received June 18, 2019; published online June 28, 2019. Assoc. Editor: Wei Chen.

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 the context of applicability. A heuristic is only useful when the context matches that at hand.

2 Related Work

2.1 Framework for Heuristics. At a fundamental level, decisions play a major role in engineering design activities [1]. Normative decision theory breaks decision-making into three main elements: identifying decision alternatives, inferring the probabilistic outcome of each alternative, and expressing the decision maker's preference regarding each outcome as a value or utility. von Neumann and Morgenstern use four axioms to express value as utility, which takes into consideration outcome uncertainty and risk preferences [2]. Using this approach, a rational decision maker chooses the alternative with the highest expected utility.

Lee and Paredis show how normative decision theory applies to design from three different perspectives: an artifact-focused, process-focused, and organization-focused perspective [3]. From the artifact-focused perspective, the designer aims to choose, from the set of all possible artifacts, the artifact that maximizes the value. From the process-focused perspective, the designer also considers the time and cost associated with the process for finding such an artifact. This process perspective leads to the conclusion that at some point, the cost of further analysis and optimization becomes larger than the expected benefit resulting from the artifact improvement. To ensure that this point is never crossed, designers resort to heuristics. Gigerenzer et al. describe heuristics as "fast and frugal" decisions using a minimum of time, knowledge, and computation [4]. Similarly, Simon observed that decision makers either find "optimum solutions for a simplified world" (the artifact-focused, design optimization perspective) or find "satisfactory solutions for a more realistic world" (the heuristic, process-focused perspective of design) [5].

The ability of heuristics to produce satisfactory results depends on how well they allow decision makers to adapt to their current environment. From the artifact-focused perspective, heuristics allow the designer to constrain the number of alternatives considered [3]. From the process-focused perspective, heuristics can help determine suitable analysis abstractions for a specific context. Heuristics can even help the designer plan which actions to consider next in the design process.

While heuristics achieve satisfactory solutions in many situations, associated biases can lead to decision-making errors [6]. Tversky and Kahneman identify many different biases occurring in commonly used heuristics. For example, the "availability heuristic" is often applied when people assess the probability of an event based on the ease or difficulty of previous occurrences coming to mind. The retrieval of prior instances may be biased by one's familiarity with the situation, the salience of the event, or assuming false correlations between two or more events. The impact of biases in our own set of heuristics can be minimized by analyzing our heuristics from a normative perspective.

Paradoxically, the use of heuristics does not negate the designer's goal to maximize the value. When considering maximization costs, the use of good heuristics leads to more preferred outcomes. The quality of a heuristic should therefore be assessed based on its ability to maximize the value [3]. Since the value of an artifact depends on not just one heuristic but on the set of all heuristics used in the design process; we should aim to choose the set of heuristics that maximizes the expected utility of the design. This chosen set of heuristics will change as the design context evolves. Just as new technologies force companies to update methods, processes, and tools, heuristics must also be updated as design contexts change [3]. Koen describes one's own set of heuristics, referred to as the "state of the art," as constantly evolving over time as new, useful heuristics are added while others become obsolete and are deleted [7].

Binder and Paredis proposed to measure the quality of a heuristic by the extent to which it supports the designer in achieving their ultimate goal, namely, to maximize the value [8]. From this value-driven design (VDD) perspective, there are no requirements placed on the system, product, or component attributes [9], but instead, a utility function is used to transform the full set of attributes into a single value score to be maximized. Therefore, a critical step for VDD is identifying measurable attributes by which the alternatives may be assessed [10]. After extracting heuristics from designers at JPL, this study offers insight into potential attributes by which we can compare heuristics from a VDD perspective.

To obtain a valid method for extracting heuristics, it is best to first formalize the definition of a heuristic. Heuristics have been studied across many disciplines, resulting in various definitions in the literature. For this study, we use a formalized definition presented by Fu et al. based on an extensive literature analysis [11]:

> *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.*

Heuristics are typically situated within a particular context and prescribe an action for the designer to take [11]. For example, consider the heuristic, "When using a bolt connection, design it to have at least one and one-half turns in the threads" (adapted from Ref. [7]). If the current design context requires a bolt connection, then the heuristic suggests the next action be constrained to choosing a bolt with one and one-half turns in the threads.

In this study, we hope to extract heuristics in this structure: A context in which the heuristic is applicable, followed by a suggested action for the designer to take: "if in context C, consider action A." If heuristics are recorded in this manner, the designer may easily identify, at each decision point, heuristics that are within the context. If more than one heuristic is applicable, the designer would ideally choose the heuristic that adds the most value to the design.

2.2 Extraction Methods for Knowledge Codification. As a first step, we extracted heuristics through interviews with designers at JPL and observed how they rely on experience and intuition to make design decisions. Our literature review of previous extraction methods includes studies focused on not just heuristics but principles and guidelines. These terms are sometimes used interchangeably in the literature, but Fu et al. cite key differences between the three [11]. Principles are considered to be fundamental rules or laws, whereas heuristics are less validated and formalized due to their reliance on intuition and experience. Guidelines have more similarities with heuristics, but guidelines still rely on more empirical evidence and are not associated with a certain "level" of success like heuristics. Heuristics, principles, and guidelines are all types of knowledge codification. While we recognize and affirm the differences among these types of knowledge codification, we also note that the existing state of the art has not yet studied the direct differences among them in terms of how extraction methods might or should vary. We hope to address this in future work. For the purposes of this paper given the current state of research, we group together the research methods for all of these types of knowledge codification, with the belief that this prior work is directly relevant and inspirational to the current pursuit. Additionally, this paper presents the extracted heuristics without attempting to distinguish between guidelines or heuristics in the results.

A series of studies performed by Daly and Yilmaz [12–18] significantly contributes to current heuristic extraction methods. Their methodology relies on protocol studies where participants think aloud while generating design solutions [12–15]. Heuristics were extracted during a coding process using sketches, notes, and verbal data generated during ideation. First, concepts generated were identified as separate solution ideas. Key characteristics and features were then identified within each concept as well as across concepts to hypothesize how the designer moved from one solution to the next [13]. Hypothesized actions potentially leading to these characteristics were considered heuristics and generalized for applicability outside the initial context [14]. Two coders worked independently to validate heuristics using inter-rater agreement. After inter-rater agreement, any remaining disagreements were discussed as a group and resolved [15]. As studies progressed, coders used heuristics from previous studies as a starting point and added new heuristics to the set as necessary [12]. The majority of protocol study participants were novice designers and students, but one large case study from Yilmaz focused on a two-year project from an expert industrial designer [16]. Similar to the protocol studies, sketches were considered separate ideas and heuristics were extracted using possible actions leading to key features of each concept.

Other studies follow similar processes but focus on products currently on the market. Yilmaz et al. extracted heuristics by hypothesizing about the actions taken by designers that led to features identified in innovative products [17]. Rather than searching across multiple sketches for key features, products were analyzed individually and then compared to other products of the same domain. Similarly, Campbell et al. identified and generalized characteristics of existing products to present design principles for the developing world [19]. Design principles were based on potential root causes of the generalized characteristics. Qureshi et al. created design guidelines for product flexibility using key design aspects uncovered by patent analysis [20].

Lastly, some studies include more hands-on or computational extraction approaches. Keese et al. added upon Qureshi's guidelines using change modes and effects analysis to identify characteristics affecting consumer product flexibility [21]. Then, potential guidelines followed to obtain those characteristics were determined. Telenko and Seepersad's eight-step method extracted environmentally conscious design guidelines using insights from dissecting products and performing life-cycle analyses [22]. Additionally, guidelines were updated based on key features of redesign concepts generated during brainstorming exercises. McComb et al. [23] use a hidden Markov model to extract heuristics from students configuring trusses and cooling systems. The model evaluates a final design to infer the probability that a hypothesized heuristic was used at one of the four steps in the design process.

When assessing extraction methods, the methods presented so far have been based on hypothesized actions and not confirmed with the designer. The previous studies using retrospective interviews following concept generation reported that the interviews had little impact on the heuristics discovered. Based on an assessment of the methods, this lack of impact may have been due to extensive time passing between the design activities and interview (years), or questions not phrased to directly ask about heuristics [12,16]. This is not to discredit previous work but instead to highlight the challenges faced when attempting to extract cognitive processes and explain how designers do design. The uniqueness and impact of the study presented in this paper are that the interview as a primary research tool allows for direct corroboration of the use of heuristics from designers. From a value-based, normative decision-making perspective, the interviews may also present insights into how we should represent relative value of heuristics in future work. Of course, as with any self-reported data, the findings are limited to the perceptions and self-awareness of the participants. A future development of this method might combine the methods of Yilmaz with ours, beginning with extraction through interview and verifying through analysis of historical design data from the participants.

In 1954, Maccoby and Maccoby defined an interview as "a face-to-face verbal exchange, in which one person, the interviewer, attempts to elicit information or expressions of opinion or belief from another person or persons" [24]. Interviews can be described on a continuum of degree of structure, from unstructured to structured. While structured interviews require strict adherence to a set interview script, unstructured interviews are free form and are guided by an objective and questions are focused on eliciting information to meet that objective [25]. A semi-structured interview, as defined by Brinkmann and Kvale, is one "with the purpose of obtaining descriptions of the life world of the interviewee in order to interpret the meaning of the described phenomena" [26]. Semi-structured interviews allow for follow-up questions as needed and give the interviewer more control to direct the conversation to elicit the desired information [25].

Gillham argues that interviews are best with small numbers of people who are accessible and necessary for the study [27]. Interviews are especially recommended when the most important questions are open and require extended responses for clarity. One final reason is for trust between the researcher and the participant. Many participants will share information in interviews that they may feel uncomfortable sharing in other situations, such as through an anonymous questionnaire, especially if the information is somewhat sensitive.

Overall, the amount of data that can be produced in interviews is the method's biggest strength [27]. This also means the transcription and analysis phases will be laborious. It is typically stated that a 1-h interview requires 10 h of transcription and a similar timeline for analysis. The preparation time for interviews is intensive to ensure all questions are open and unbiased, and the researcher must practice the use of prompts and probing beforehand. Prompts allow the researcher to cover all of the topics that are expected to come up in the interview, without leading or indicating an answer to them. Probing during semi-structured interviews needs to sound natural and may motivate the participant to elaborate more on a topic. In general, the ability to keep the interview flowing is a necessary skill for the interviewer.

Saldana highlights three crucial mistakes commonly found in interview design [28]. First, constructing closed-ended questions can lead to one-word responses without critical insight. It is not a good practice to assume the participant will always elaborate after a yes/no response. Second, the participant can feel overwhelmed when asked multiple questions in a single prompt. This can weaken the responses. Lastly, asking either/or questions may lead to limiting responses and prevent the full insight of an event. Researchers are highly susceptible to these last two issues when improvising or asking follow-up questions during the interview, so it is important to practice all scripted questions before the study. Outside of the questions, any power dynamics felt between the participant and the researcher can also have an impact on the study. It is recommended to create a comfortable atmosphere that promotes a balanced relationship. One way to do this through the interview structure is to present the background and purpose of the interview, so the participant understands its significance. Similarly, it is best to get necessary background information from the participant early in the interview before moving to more in-depth questions.

The interviews conducted in this work were designed to avoid these issues by having each question force the participant to reflect on which heuristics they use and how they are implemented in their own words. Questions seeking specific characteristics of a heuristic are saved until the end of the interview, so the participant is not overwhelmed during the heuristic generation portion of the interview. Some portions of the script include multiple ways to phrase the same question in case a participant gets stuck in the interview. These are not meant to be used unless necessary, and they do not request any new information for the initial prompt. All "either/or" questions have been eliminated from the script and avoided in any follow-up questions during the interview. To keep the relationship between the researcher and the participant at ease, the study begins with background information from both sides. Sharing the motivation should help the participant understand their significance to the research and sharing their own background with the researcher should make them comfortable before moving to more detailed questions relating to heuristics.

Eckert and Summers presented an overview of interviews as a research tool in engineering design [29]. While some studies have used interviews as a primary method of data collection, other purposes include providing verification, motivation, explanation, or evaluation. Popular reasons to apply interviews include understanding complex systems and verifying results through triangulation. For example, Almefelt et al. used interviews to study requirements management processes during cockpit design [30]. The interviews were the third leg of triangulation, where the other two methods included a visual product study and document analysis. Achiche et al. also used a three-step process including interviews with follow-up questionnaires [31]. After an initial gathering of information, company managers were interviewed to discuss contexts, processes, inputs, and outputs relative to core front-end design tools. A follow-up questionnaire allowed for more input on the parameters discussed during interviews. In the same manner, this study builds upon interview data using follow-up surveys. To the best of our knowledge, this is the first known application of interviews and surveys as primary methods for extracting and characterizing design heuristics.

Creswell describes the goals of survey research design as obtaining the attitudes, opinions, behaviors, or characteristics of the population [32]. Surveys can be taken within a population at one point in time (cross-sectional) or over an extended period (longitudinal). They can also come in the form of open-ended, closed-ended, or semi-closed-ended questions. Closed-ended questions have a predetermined set of responses for the participant to choose from. Participants are typically comfortable answering closed-ended questions, and they also ease the workload of coding and comparing responses. Semi-closed-ended questions allow the option to write a unique response if the predetermined set do not meet the participant's desired response. This style helps reduce the constraints set on the participant while maintaining a convenient set of responses for analysis. The survey in this study is a cross-sectional survey in the form of a questionnaire, where participants complete the form and return it to the researcher. This transaction was done through a web-based questionnaire. The survey was a mixture of closed-ended questions and semi-closed-ended questions.

Creswell also presents ten common problems found in the survey design. These issues were considered when designing the survey. For example, one mistake involves using jargon that is unfamiliar to some participants. In this study, the idea of concept maturity levels is not common knowledge outside of the A-Team. It is possible that members with different levels of experience have had different levels of exposure to this concept. Therefore, the surveys included an infographic explaining each concept maturity level (CML) so that all participants clearly understood which heuristics were or were not applicable to each CML. All ten mistakes to avoid can be found in Table 1, along with the process for avoiding the mistake followed in this work.

Krosnick and Presser present the goal of the survey design as having participants that give optimizing responses rather than satisficing responses [33]. Optimization occurs when respondents are motivated to answer questions in a thorough and unbiased manner. Anything short of this can be called "satisficing." Satisficing can exist through three main factors: task difficulty, respondent ability, and respondent motivation. Therefore, researchers should aim to minimize task difficulty and maximize respondent motivation in the survey. Task difficulty can be affected by effort required for question interpretation, memory recall, and responding. Motivation can be maximized by ensuring the participant avoids survey fatigue and understands the survey's personal importance and useful consequences.

In the survey conducted here, the researchers attempt to minimize task difficulty by making each question as simple as possible. For memory recall, the researchers hope that designers can easily recall the heuristics discussed during each interview. The end of each interview contained questions like the survey, in hopes of preparing participants to give similar responses for all heuristics from their respective interviews. Lastly, a 5-point Likert scale was used

Table 1 Common survey issues and methods used for improvement

Common survey issues	Issue avoidance
The question is unclear	Questions were reviewed by experts
There are multiple questions within a question	Questions included one heuristic attribute per question
The question is too wordy	Questions excluded all unnecessary phrases
The question is negatively worded	All questions were positively worded
The question includes jargon	The survey included an infographic for JPL terminology
There are overlapping responses	The survey included Likert scale responses
There are unbalanced response options	The survey included Likert scale responses
The question and answers are mismatched	The survey used consistent action verbs between questions and responses
The questions are overly technical	Each survey was tailored to the heuristics of the participant to ensure familiarity of subject
The questions do not apply to all participants	Each survey was tailored to each participant based on the interview

for most responses, following Krosnick's claim that a moderately sized point scale with a midpoint may improve rating reliability and validity, although there is no standard scale size across researchers. Too few points on the scale can increase difficulty for respondents to express their true view towards an issue while too many points on the scale can make it difficult to interpret where they fall along the scale. Finally, the attempt to maximize motivation was done by giving surveys with heuristics specific to their design experiences and explaining in the interview how a better understanding of their own heuristics can improve their future design processes.

2.3 Classification Methods for Knowledge Codification. Classifying heuristics can be beneficial for reducing the number of plausible heuristics necessary to consider based on the context or desired actions. Studies from Yilmaz and Daly split heuristics into three different categories: local heuristics, transitional heuristics, and process heuristics [14,15,17]. Local heuristics affect characteristics within a single concept while transitional heuristics aid a designer's transition from one concept to the next. Process heuristics more broadly prompt a designer's general problem-solving approach [15]. These three areas express the intent of the heuristic during idea generation. Overall, heuristics collected over the course of four major studies by Yilmaz and Daly were catalogued and commercialized as the 77 design heuristics [18]. Each heuristic comes with a description for application along with an example of its use in commercial products.

In other studies, Singh et al. classified "Design for Transformation" principles using two categories: principles and facilitators [34]. Qureshi et al. separated guidelines by four general approaches to flexibility [20]. Moe et al. [35] classified prototype partitioning strategies by breaking down the design context. Partitioning strategies are recommended based on the flexibility of cost, schedule, and performance. Lee et al. used a similar method to classify robotics design heuristics by breaking down the context into design phase, field of study, and action intent [36]. Subcategories for design phase and action intent were derived from Pahl et al. classifications [37]. The classifications in all of these studies reduce the number of actions considered for a designer's next decision in the design process.

Some studies provide more insight into the processes taken to create the categories used to organize data. Telenko et al. developed a classification scheme for design for environment guidelines using mind-mapping, a visual representation of brainstorming [38]. Reap and Bras categorized biological principles using a portion of grounded theory's constant comparative method (CCM) [39]. CCM allows researchers to extract and analyze qualitative data simultaneously. Instead of simply describing the data, the coder identifies relationships within and across the data [40]. By comparing patterns, themes, similarities, or differences, categories are generated that provide more explanation to the data. Reap and Bras finalized each category using descriptions and reasoning for development [39].

Heuristics can be "found" and used more effectively if they are organized in a way that aids a designer's understanding of how and when the heuristics should be applied to their own design problems. This paper aims to build on previous studies by classifying heuristics extracted from members of JPL's A-Team. The goal is to find an appropriate categorization of heuristics that allows expert participants to correctly specify their current design situation and reduce the number of heuristics considered for the next design action. The scope of this study will only provide an initial attempt at categorization, while future work may include testing to identify the most effective categorization to be applied in industry/classroom settings.

2.4 JPL Innovation Foundry. The participants of this study are engineers associated with JPL's A-Team. JPL is one of NASA's federally funded research and development centers [41]. 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 new 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.

The CML scale measures the maturity of deep space mission concepts [41]. 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 [42,43]. 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 [41,42,44]. 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 [42]. This usually includes high-level objectives, science questions, the science for addressing those questions, and a "cocktail napkin" sketch of the mission concept [44]. 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 [42]. The trade study explores impacts on science return, cost, and risk [44].

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 [45]. An entire A-Team study lasts about six weeks, beginning with client meetings [46]. Background information, goals, and requirements for the study are discussed at length during the client meeting [45]. 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 [46]. Studies take place in a designated area named "left field", filled with reference material and whiteboards to promote creativity [47]. 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 [47]. Sometimes, the facilitator may be the study lead [45]. 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 [47]. 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 a great 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 [41]. 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 [48]." 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 [48]." 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 Methodology

The goal of this study[1] was to extract heuristics used in the A-Team setting at JPL using interviews as the primary method for gathering data. One of the authors attended an A-Team study at JPL to relay the details of the experiment to A-Team members. Any member(s) who wanted to volunteer for the study was required to sign a consent form. 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 10 participants interviewed average 16 years of engineering experience, 10 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 and 30 years old, three between 31 and 40 years old, three between 51 and 60 years old, and one between 61 and 70 years old. Six participants were

[1]The research plan received an Institutional Review Board (IRB) approval for human subject research.

system 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 1 h 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.

3.1 Part 1: Understanding Heuristics. In the first 10–15 min 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* [49] 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 2.

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 min 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 versus redesign), phase of the design process, or area of application. Some example excerpts from the interview transcripts are presented next.

Table 2 Example heuristics used for interviews

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

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 the 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 to 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 research 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 Part 3: Characterizing Heuristics. For the final 10–15 min 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 10 min 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, and 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.

4 Results and Discussion

From the 10 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. For brevity, the total set of heuristics could not be published in this paper. Interested researchers can contact the corresponding author to obtain the full set of heuristics collected in this study.

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 (63 total), and in-person interviews averaged 7.6 heuristics per person (38 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 in Table 3.

Table 3 Quantity of heuristics by participant

Participant	Number of heuristics	Interview type
A	11	Phone
B	8	Phone
C	15	Phone
D	18	Phone
E	Excluded (did not complete survey)	Phone
F	11	Phone
G	9	In-person
H	10	In-person
I	7	In-person
J	9	In-person
K	3	In-person

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 Table 4. 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 Table 4, 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 [50]. Action intent uses similarities in suggested actions from the data and draws on our previous work using design phases from Lee et al. [36] and Pahl et al. [37].

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 [41,42]. 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 [14,38]. The classifications that followed were designed to describe how these goals are achieved. For example, Daly showed how transitional heuristics generate ideas by building off existing concepts. The classification in our 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.

4.2 Survey Results. The survey results and analysis are presented in Figs. 1–8 and give insight into potential characterization and evaluation of heuristics. Figure 1 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

Table 4 Heuristic classification scheme

Primary area of concern	Secondary area of concern	Action intent	Example heuristic
A-Team study design (27)	Prestudy planning (12)	Create schedule/timeline (11)	When presenting topics relevant to the study, keep the presentations short (about 10–15 min)
		Identify resources required (1)	When planning an A-team session, design the study to have between 8 and 12 people
	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 multivote system rather than one vote per person
Mission design (29)	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
	Cost (9)	Estimate cost (7)	For missions with clear science goals, find the expected cost using the expected mass required to meet those goals
		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
Spacecraft design (45)	Payload (2)	Instrument design (2)	For an inner planet mission, plan to fit Y number of instruments on the spacecraft
	System requirements (21)	Estimate power required (7)	When designing a mission, find the expected power by determining the instruments required to meet the science goals
		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
	Subsystem requirements (22)	Power (9)	When choosing the power source, choose based on the mission location
		Propulsion (8)	When landing on a body with high gravity, stage the propulsion
		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 and orbit control (1)	If the mission location has a strong environmental force, use a balanced spacecraft to make the attitude control less massive
		Structure and mechanisms (2)	When designing a mission, consider putting multiple functions, such as an orbiter and a lander, onto one element

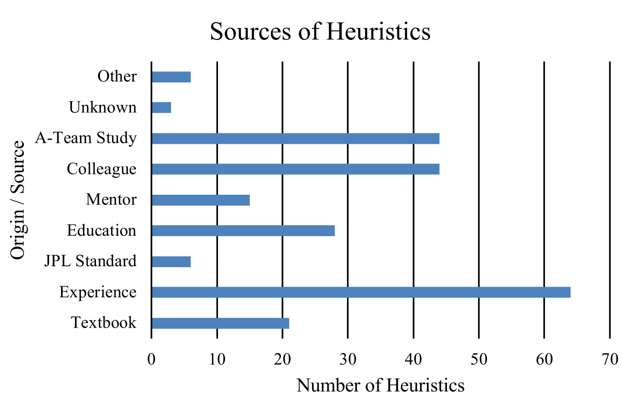

Fig. 1 Origin/source of heuristics

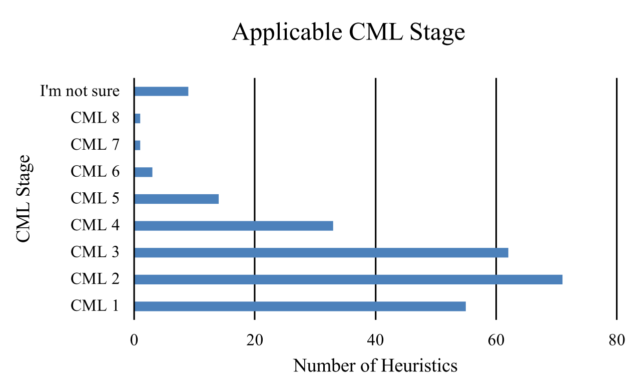

Fig. 2 Applicable CML stage for heuristics

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.

Figures 2 and 3 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 two of the three.

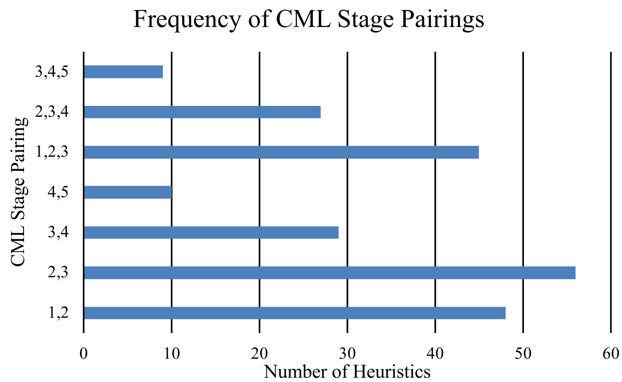

Fig. 3 Most common CML pairings for a heuristic

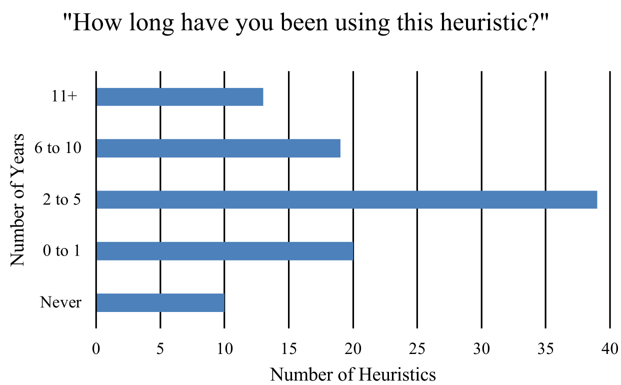

Fig. 4 How long each heuristic has been in use

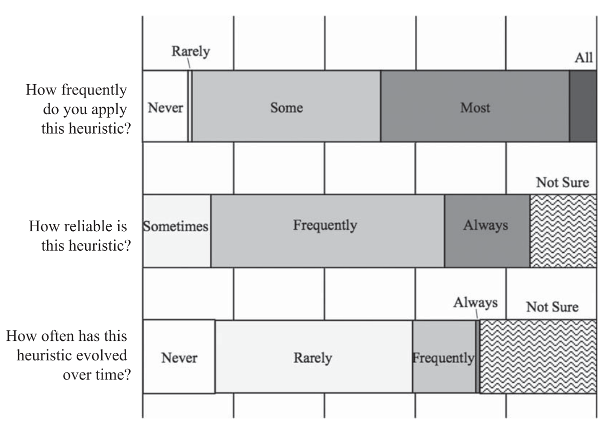

Fig. 5 Self-reported evaluations of heuristics

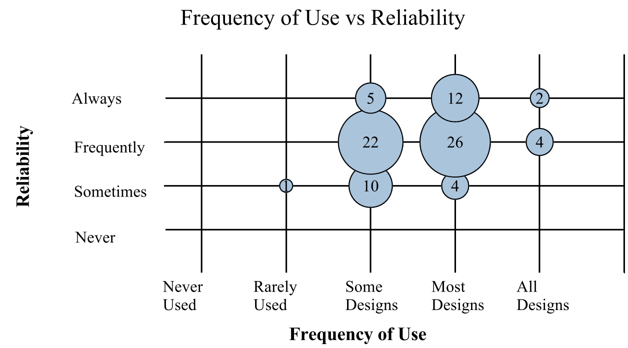

Fig. 6 Self-reported combinations for frequency and reliability

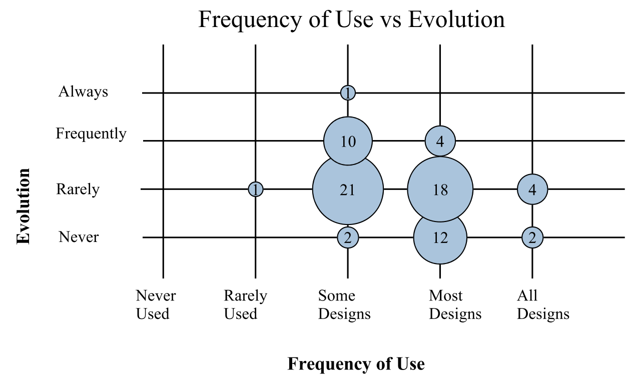

Fig. 7 Self-reported combinations for frequency and evolution

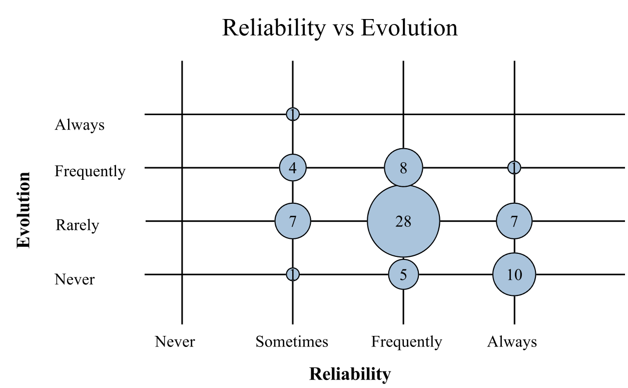

Fig. 8 Self-reported combinations for reliability and evolution

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.

Figure 4 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, these 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 Secs. 5 and 6.

Figure 5 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.

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 was 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 were ordinal, which makes a Pearson's correlation inappropriate [51]. Results from 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 is shown in Fig. 6. Spearman's correlation coefficient of 0.305 shows that this relationship has a positive correlation. This means when the heuristic is used more frequently, the reliability tends to increase. This correlation has two-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 as follows:

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 7 shows combined survey responses for frequency of use and evolution of a heuristic. Spearman's correlation coefficient of −0.385 shows that this relationship has a negative correlation. This means a heuristic used more often also tends to evolve less often. This correlation has two-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 defeat one purpose of the heuristic itself to save processing time. Examples of heuristics on each end of the scale are presented as follows:

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 8 shows combined survey responses for reliability and evolution of a heuristic. Spearman's correlation coefficient of −0.435 shows that this relationship has a negative correlation. This means a more reliable heuristic tends to evolve less often. This correlation has two-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 as follows:

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.

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 4×3 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 [35].

5 Conclusions

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 paper 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 our 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, and 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 preexisting 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.

6 Limitations and Future Work

There are a number of limitations to this work, discussed next. Sufficient interviews have not been conducted to reach saturation, and many more participants, from more representatively distributed demographics, are needed to have results that are more generalizable. This sample represented approximately half of the A-Team members. However, this expert level, rich data are highly valuable, even with the relatively small sample size, and especially given the qualitative nature of the study. Improvement of the methodology may begin through better understanding of any "not sure" responses within the survey data. The reliance on self-reported data of evaluations of heuristics is a limitation of the survey data. However, direct corroboration of heuristics and their characteristics from the designer is a benefit to this approach that is not present in purely observational studies of heuristics. The interview format only collected heuristics that designers were actively aware of, but additional studies may review previous A-Team study documents or observe a live A-Team study session to find heuristics the designers could not recall during interviews to strengthen the pool of heuristics for analysis. Eventually, we hope to externally assess the heuristics through a rigorous mathematical framework, omit any internal bias, and move towards a justified use of heuristics from a normative perspective. To do this, additional attributes not explored in this paper may also be identified to present information separating one heuristic from another during decision-making. In addition, a formal language or ontology will likely need to be established to translate and relate heuristics within a repository.

In establishing a shared understanding of the definition of heuristic, individual examples of heuristics were introduced by the interviewer. There is potential that this could have created a priming bias or fixation in the interviewee, making them more prone to discuss or recall similar types of heuristics to the examples discussed. This type of potential bias is at times unavoidable when attempting to establish a shared definition of a concept.

Based on the new understanding of the nature of heuristics, their use, their characteristics, and methods to extract and confirm them, the following new research objectives have arisen:

- What characteristics, beyond frequency of use, reliability of success, and rate of evolution, can be used to assign value to a heuristic?
- How can unconscious heuristics be extracted from designers? How can these unconscious heuristics be corroborated by designers?
- How can direct observation be combined with interview and survey data collection methods to achieve empirically derived heuristics that can be corroborated by designers? How can further triangulation of results be added to the research method design?
- How should the methods for design heuristic extraction vary from design guideline extraction or design principle extraction?

Future work may strengthen the data by expanding our understanding of the reasoning behind "years of use" survey responses and obtaining more information for how or why a heuristic has evolved. Additional interviews may ask about each heuristic in more detail, such as asking participants more in-depth questions about the last time they have used the heuristic. This may lead to insights not yet discovered for representing the relative value of heuristics. The classification may be improved into an adequate guide for the A-Team, although any additional classification levels, such as mission location and spacecraft type, may require more information for each heuristic to have significant impact. A future repository could benefit from specific examples of when a heuristic was or was not used, or through exploring how similar heuristics are perceived and presented differently across designers. A-Team-specific heuristics can be generalized for application of other domains, although process-focused heuristics may be more broadly applicable than artifact-focused heuristics limited to spacecraft design. In either case, it is important to maintain the true nature of the heuristic.

Acknowledgment

The research presented in this paper was supported in part by the National Science Foundation (Award CMMI-1645316; Funder ID: 10.13039/501100001809). The United States Government retains, and by accepting the article for publication, the publisher acknowledges that the United States Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work or allow others to do so, for United States Government purposes. This work was also supported in part by the Georgia Tech Center for Space Technology and Research (CSTAR) Summer Fellowship Program. We would like to sincerely thank the Jet Propulsion Lab and the members of the A-Team for their participation in and support of this research.

Appendix: Semi-Structured Interview Script

(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 our 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:
    (i) 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:
  (a) Example 1 - nitty gritty
    (i) "When using a bolt connection, design it to have at least one and one-half turns in the threads"
  (b) 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.
  (c) 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 earth-oriented, use a gravity gradient technique for guidance and control.
    (iv) Propulsion: To reach low earth orbit, allow for a delta-v of around 10 km/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?

References

[1] Lewis, K. E., Chen, W., and Schmidt, L. C., 2006, *Decision Making in Engineering Design*, ASME, New York, NY.
[2] von Neumann, J., and Morgenstern, O., 2004, *Theory of Games and Economic Behavior*, 60th ed. (Princeton Class Editions), Princeton University Press, Princeton, NJ.
[3] Lee, B. D., and Paredis, C. J. J., 2014, "A Conceptual Framework for Value-Driven Design and Systems Engineering," 24th CIRP Design Conference: Mass Customization and Personalization, Vol. 21, Milano, Italy, Apr. 14–16, pp. 10–17.
[4] Gigerenzer, G., Todd, P. M., and ABC Research Group, 1999, *Simple Heuristics That Make Us Smart*, Oxford University Press, New York.
[5] Simon, H. A., 1979, "Rational Decision Making in Business Organizations," Am. Econ. Rev., **69**(4), pp. 493–515.
[6] Tversky, A., and Kahneman, D., 1974, "Judgement Under Uncertainty: Heuristics and Biases," Science, **185**(4157), pp. 1124–1131.
[7] Koen, B. V., 1985, *Definition of the Engineering Method*, American Society for Engineering Education, Washington, DC.
[8] Binder, W. R., and Paredis, C. J. J., 2017, "Optimization Under Uncertainty Versus Algebraic Heuristics: A Research Method for Comparing Computational Design Methods," ASME 2017 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Cleveland, OH, Aug. 6–9, pp. 1–10.
[9] Collopy, P. D., and Hollingsworth, P. M., 2011, "Value-Driven Design," J. Aircr., **48**(3), pp. 749–759.
[10] Sage, A. P., and Armstrong, J. E., Jr., 2000, *Introduction to Systems Engineering (Wiley Series in Systems Engineering)*, John Wiley & Sons, Inc., New York.
[11] Fu, K. K., Yang, M. C., and Wood, K. L., 2016, "Design Principles: Literature Review, Analysis, and Future Directions," ASME J. Mech. Des., **138**(10), p. 101103.
[12] Daly, S. R., Yilmaz, S., Christian, J. L., Seifert, C. M., and Gonzalez, R., 2012, "Design Heuristics in Engineering Concept Generation," J. Eng. Educ., **101**(4), pp. 601–629.
[13] Yilmaz, S., Daly, S. R., Seifert, C. M., and Gonzalez, R., 2014, "How Do Designers Generate New Ideas? Design Heuristics Across Two Disciplines," Des. Sci., **1**(4), pp. 1–29.
[14] Daly, S., Yilmaz, S., Seifert, C., and Gonzalez, R., 2010, "Cognitive Heuristic Use in Engineering Design Ideation," 2010 Annual Conference & Exposition, Louisville, KY, June 20, ASEE Conferences, pp. 1–25.
[15] Yilmaz, S., Daly, S. R., Seifert, C. M., and Gonzalez, R., 2011, "A Comparison of Cognitive Heuristics Use Between Engineers and Industrial Designers," 4th International Conference on Design Computing and Cognition '10, Stuttgart, Germany, July 12–14, pp. 3–22.
[16] Yilmaz, S., and Seifert, C. M., 2011, "Creativity Through Design Heuristics: A Case Study of Expert Product Design," Des. Stud., **32**(4), pp. 384–415.
[17] Yilmaz, S., Seifert, C., Daly, S. R., and Gonzalez, R., 2016, "Design Heuristics in Innovative Products," ASME J. Mech. Des., **138**(7), p. 071102.
[18] Yilmaz, S., and Daly, S. R., 2016, "Evidence-Based Design Heuristics for Idea Generation," Des. Stud., **46**, pp. 95–124.
[19] Campbell, R. D., Lewis, P. K., and Mattson, C. A., 2011, "A Method for Identifying Design Principles For the Developing World," ASME 2011 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Washington, DC, Aug. 28–31, pp. 1–8.
[20] Qureshi, A., Murphy, J. T., Kuchinsky, B., Seepersad, C. C., Wood, K. L., and Jenson, D. D., 2006, "Principles of Product Flexibility," ASME 2006 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Philadelphia, PA, Sept. 10–13, pp. 1–31.
[21] Keese, D. A., Tilstra, A. H., Seepersad, C. C., and Wood, K. L., 2007, "Empirically-Derived Principles for Designing Products With Flexibility for Future Evolution," ASME 2007 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, Las Vegas, NV, Sept. 4–7.
[22] Telenko, C., and Seepersad, C. C., 2010, "A Methodology for Identifying Environmentally Conscious Guidelines for Product Design," ASME J. Mech. Des., **132**(9), pp. 1–9.
[23] McComb, C., Cagan, J., and Kotovsky, K., 2017, "Mining Process Heuristics From Designer Action Data Via Hidden Markov Models," ASME J. Mech. Des., **139**(11), pp. 1–12.
[24] Maccoby, E. E., and Maccoby, N., 1954, "The Interview: A Tool of Social Science," *Handbook of Social Psychology*, G. Lindzey, ed., Addison-Wesley, Cambridge, MA, pp. 449–487.
[25] Brinkmann, S., 2017, "The Interview," *The SAGE Handbook of Qualitative Research*, 5th ed., N. K. Denzin, Y. S. Lincoln, eds., SAGE, Los Angeles, CA, pp. 576–600.
[26] Brinkmann, S., and Kvale, S., 2015, *InterViews: Learning the Craft of Qualitative Research Interviewing*, 3rd ed., Sage, Thousand Oaks, CA.
[27] Gillham, B., 2000, *Case Study Research Methods*, 1st ed. (Continuum Research Methods Series), Bloomsbury Publishing PLC, London.
[28] Saldana, J., 2011, *Fundamentals of Qualitative Research*, Oxford University Press, OSO, New York, NY.
[29] Eckert, C., and Summers, J., 2013, "Interviewing as a Method for Data Gathering in Engineering Design Research." Clemson University. https://cecas.clemson.edu/cedar/wp-content/uploads/2016/07/6-2013-06-14-Eckert-Summers-Interviewing-final.pdf
[30] Almefelt, L., Berglund, F., Nilsson, P., and Malmqvist, J., 2006, "Requirements Management in Practice: Findings From an Empirical Study in the Automotive Industry," Res. Eng. Des., **17**(3), pp. 113–134.
[31] Achiche, S., Appio, F. P., McAloone, T. C., and Minin, A. D., 2013, "Fuzzy Decision Support for Tools Selection in the Core Front End Activities of New Product Development," Res. Eng. Des., **24**(1), pp. 1–18.
[32] Creswell, J. W., 2012, *Educational Research: Planning, Conducting, and Evaluating Quantitative and Qualitative Research*, 4th ed., Pearson Education, Inc., Boston, MA.
[33] Krosnick, J. A., and Presser, S., 2010, "Question and Questionnaire Design," *Handbook of Survey Research*, 2nd ed, P. V. Marsden, J. D. Wright, eds., Emerald Group Publishing Limited, Bingley, UK, pp. 264–313.
[34] Singh, V., Skiles, S. M., Krager, J. E., and Wood, K. L., 2006, "Innovations in Design Through Transformations: A Fundamental Study of Transformation Principles," ASME 2006 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, Philadelphia, PA, Sept. 10–13, pp. 1–14.
[35] Moe, R. E., Jenson, D. D., and Wood, K. L., 2004, "Prototype Partitioning Based on Requirement Flexibility," ASME 2004 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Salt Lake City, UT, Sept. 28–Oct. 2, pp. 1–13.
[36] Lee, B., Fillingim, K. B., Binder, W. R., Fu, K., and Paredis, C. J. J., 2017, "Design Heuristics: A Conceptual Framework and Preliminary Method for Extraction," Paper Presented at the ASME 2017 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Cleveland, OH, Aug. 6–9, pp. 1–10.
[37] Pahl, G., Beitz, W., Feldhusen, J., and Grote, K. H., 2007, *Engineering Design: A Systematic Approach*, 3rd ed., Springer, New York.
[38] Telenko, C., O'Rourke, J. M., Seepersad, C. C., and Webber, M. E., 2016, "A Compilation of Design for Environment Guidelines," ASME J. Mech. Des., **138**(3), pp. 1–11.
[39] Reap, J., and Bras, B., 2014, "A Method of Finding Biologically Inspired Guidelines for Environmentally Benign Design and Manufacturing," ASME J. Mech. Des., **136**(11), pp. 1–11.
[40] Goulding, C., 2002, *Grounded Theory: A Practical Guide for Management, Business, and Market Researchers*, 1st ed., Sage Publications Inc., Thousand Oaks, CA.
[41] Sherwood, B., and McCleese, D., 2013, "JPL Innovation Foundry," Acta Astronaut., **89**, pp. 236–247.
[42] Leising, C. J., Sherwood, B., Adler, M., Wessen, R. R., and Naderi, F. M., 2010, "Recent Improvements in JPL's Mission Formulation Process," Paper Presented at the IEEE Aerospace Conference, Big Sky, MT, Mar. 6–13, pp. 1–12.
[43] Wessen, R. R., Adler, M., Leising, C. J., and Sherwood, B., 2009, "Measuring the Maturity of Robotic Planetary Mission Concepts," Paper Presented at the AIAA SPACE 2009 Conference & Exposition, Pasadena, CA, Sept. 14–17, pp. 14–17.
[44] Wessen, R. R., Borden, C., Ziemer, J., and Kwok, J., 2013, "Space Mission Concept Development Using Concept Maturity Levels," Paper Presented at the AIAA Space 2013 Conference and Exposition, San Diego, CA, Sept. 10–12, pp. 1–18.
[45] Ziemer, J. K., Ervin, J., and Lang, J., 2013, "Exploring Mission Concepts With the JPL Innovation Foundry A-Team," Paper Presented at the AIAA SPACE 2013 Conference and Exposition, San Diego, CA, Sept. 10–12, pp. 1–13.
[46] Ziemer, J. K., Wessen, R. R., and Johnson, P. V., 2016, "Exploring the Science Trade Space With the JPL Innovation Foundry A-Team," Paper Presented at the SESCA 2016, Madrid, Spain, Oct. 5–7, pp. 1–9.
[47] Linsey, J., Wessen, R., and Ziemer, J., 2016, "Observation of a Highly Innovative Group—Directions for Future Research," The Fourth International Conference on Design Creativity, Atlanta, GA, Nov. 2–4, pp. 1–9.
[48] Mills, A. J., Durepos, G., and Wiebe, E., 2010, *Encyclopedia of Case Study Research*, SAGE Publications, Inc., Thousand Oaks, CA.
[49] Wertz, J. R., and Larson, W. J., 1999, *Space Mission Analysis and Design*, 3rd ed., Microcosm Press, Kluwer Academic Publishers, Dordrecht.
[50] Fortescue, P., Stark, J., and Swinerd, G., 2003, *Spacecraft Systems Engineering*, John Wiley & Sons Ltd., Chichester, West Sussex.
[51] Hauke, J., and Kossowski, T., 2011, "Comparison of Values of Pearson's and Spearman's Correlation Coefficients on the Same Sets of Data," Quaestiones Geographicae, **30**(2), pp. 87–93.