Process Heuristics: Extraction, Analysis, and Repository Considerations

Kenton B. Fillingim, Hannah Shapiro, Christiaan J. J. Paredis, and Katherine Fu

***Abstract*—The motivation for this article is to present a method for extracting heuristics from a team of mission architects, referred to in this article as "designers" at NASA's Jet Propulsion Laboratory (JPL). The method for this study includes both focus group and individual interviews, as well as artifact analysis. The interviews led to insights about the role of heuristics within a design team and how documenting those heuristics can be of value to the team. The heuristics generated allowed for an overview of how designers at JPL perceived their own process heuristics. It was found that most heuristics were comprised a single, positively framed step to be carried out within the team, not just by an individual. Participants were also able to produce mainly informal actions they take, rather than formalized textbook approaches to design. It is hypothesized that the process heuristics generated are universal enough to be transferred out of the mission design domain and into another, if desired.**

***Index Terms*—Complex systems, design engineering, design methodology, process design, psychology, system analysis and design.**

I. Background

A. History of Heuristics and Biases

In PSYCHOLOGY and economics, heuristics are known as "procedures for problem solving that function by reducing the number of possible alternatives and solutions and thereby increasing the chances of a solution" [1]. They are a means for simplifying information processing. In engineering, Koen defined heuristics as strategies that are potentially fallible but give direction toward solving a problem [2]. They are used by the designer to guide, discover, and reveal. They do not guarantee solutions, may contradict other heuristics, reduce search time, and depend on the context rather than an absolute standard. Using these characteristics, Koen argued that "all engineering is heuristic." Fu *et al*. [3] analyzed many different definitions of heuristics and presented a composite definition of heuristics in design as "a context-dependent directive, based on intuition, tacit knowledge, or experiential understanding, which provides design process direction to increase the chance of reaching a satisfactory but not necessarily optimal solution."

Historically, heuristics have been often viewed in contrast to other prescriptive decision-making methods. The "rational" decision-making model began with von Neumann and Morgenstern [4] using a set of axioms to assign outcomes of an event with a value known as utility. Utility theory considers the uncertainty of the event, as well as the decision maker's risk preferences. From the perspective of the utility theory, a rational decision maker should make decisions connected to the highest expected utility. Howard [5] assisted in the development of "Decision Analysis" by combining utility theory with Bayesian statistics, a way to update probabilities given new information. For some time, it was assumed that humans naturally make decisions in a manner consistent with these models. For example, Friedman and Savage [6] hypothesized that it is realistic to assume people have consistent preferences that could be described by a utility, with the objective to make this utility as large as possible. They use an expert billiards player as an example: while the player may not know or perform all the mathematical equations behind each potential shot, they will consistently choose the shot they believe will most likely result in the preferred outcome.

Tversky and Kahneman [7] led the way in presenting how humans rely on heuristics that can bias decision making such that the decisions are not consistent with utility theory. One well noted example is the "representativeness" heuristic, in which people will evaluate probabilities based on similarities. The probability that A belongs to B is evaluated by the degree to which A resembles B. This process may result in severe errors in judgment when factors, such as prior probability or sample size, are not considered. As an example, Tversky and Kahneman [7] described a hypothetical individual, Steve, as shy, tidy, meek, and having a passion for order. They then asked subjects to judge which profession Steve is likely to hold, among farmer, salesman, airline pilot, librarian, or physician. They found that "the probability that Steve is a librarian, for example, is assessed by the degree to which his is representative of, or similar to, the stereotype of a librarian," rather than the relative proportion of the population that comprises librarians. Tversky and Kahneman [7] did not intend for heuristics to prove humans behave irrationally, but rather to show that the existing models of rationality did not accurately describe humans [5], [8].

Other researchers attempt to justify heuristics as a rational form of decision making, particularly when viewed from an evolutionary standpoint. Haselton *et al*. [9] suggested natural selection has allowed humans to deploy heuristics in a way that best

Manuscript received August 5, 2019; revised September 19, 2019; accepted December 6, 2019. This work was supported in part by the Georgia Institute of Technology Center for Space and Technology Research (CSTAR) Strategic Fellowship and in part by Government sponsorship. The work of K. Fu was supported by National Science Foundation under Grant CMMI 1645316. *(Corresponding author: Katherine Fu.)*

K. B. Fillingim, H. Shapiro, and K. Fu are with the School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332 USA (e-mail: blane.fillingim@gatech.edu; hshapiro28@gatech.edu; katherine.fu@me.gatech.edu).

C. J. J. Paredis is with the Department of Automotive Engineering, Clemson University, Greenville, SC 29607 USA (e-mail: paredis@clemson.edu).

Digital Object Identifier 10.1109/JSYST.2019.2959538

serves the "fitness" of humans over time. Lo [10] also viewed heuristics as developed for survival in a particular environment. For example, heuristics developed by investors during the great depression would differ from those in a booming economy. It would not be fair to consider either sets of heuristics irrational, because they were shaped to survive a specific economic environment. As this environment changes, the heuristics may no longer be beneficial, and new heuristics must be acquired.

Gigerenzer [11] believed heuristics can exist as a rational decision-making tool alongside logic and probability theory, where each tool is valid given the right environment. The heuristics have "ecological rationality" in situations where they are not just cognitive limitations, but allow for better decision making in situations in which other methods may struggle. For example, the "1/*N*" heuristic (allocating money equally to *N* number of assets in an investment portfolio) has been shown to perform better than the portfolio optimization proposed by Markowitz, when the environment contains large uncertainty, many assets, and smaller learning samples.

The history of decision making is relevant to this article for its ability to place relative value on each decision alternative in question. The authors believe that this framework can be extended to heuristics for justifying when one heuristic should be used over another, if the heuristics are documented and described in a sufficient manner. Gigerenzer believed the results from Tversky and Kahneman [7] were limited because they failed to address the environment in which heuristics (such as the *representativeness* heuristic) performed adequately or poorly [12]. This was not to discredit their work, but rather to emphasize the importance of context when considering heuristics in place of other decision-making tools. Following a similar motivation, Binder provides an updated framework for presenting heuristics by pairing a *context* in which the heuristic is applicable to a set of potential *actions* to be taken [13]. In mission formulation, referred to in this article as "design," an example heuristic in this form may be, "If the space mission is to an outer planet (context), use a nuclear power source (action)." This is the format used for presenting heuristics in this article, as the authors believe understanding the proper contexts in which a heuristic should be used is a crucial first step in determining the value of a heuristic.

B. Process Heuristics

In a previous study by the authors, an overwhelming majority of heuristics generated were focused directly on the artifact, similar to the previous example heuristic for choosing a spacecraft power source [14]. The study presented in this article will focus specifically on obtaining insight into how experts view their own process heuristics. Process heuristics are those that guide the design process, rather than the direct design of the details of an artifact. For example, a process heuristic may be "when aiming to generate novel systems concepts, consider using brainwriting." Brainwriting uses "naturally occurring ideas, without judgment, as starting points for concepts" [15]. Based on the definitions and characteristics previously presented, this is a process heuristic because the hypothetical designer understands when to implement the brainwriting technique as a guide toward a design solution. While brainwriting may not guarantee the most valuable concept available, a designer may believe from experience that its implementation will generate at least one idea considered satisfactory. Yilmaz *et al*. [15] differentiated process heuristics from "local" or "transitional" heuristics to be those that define relationships in one concept or transform a current concept to a new concept. An example of this is the "Substitute" heuristic—which may be written as "when aiming to improve an artifact/system, consider substituting a design characteristic, such as material, with another that accomplishes the same function."

Barclay and Bunn [16] defined process heuristics as consistent with the editing stage of Kahneman and Tversky's [17] prospect theory because they assist with "deciding how to decide". Prospect theory describes individual decision making in two phases: an editing phase and an evaluation-decision phase. The editing phase manipulates prospects to simplify the evaluation-decision phase. Editing operations are meant to facilitate the task of decision making. An example process from Kahneman and Tversky [17] is the *cancellation* operation, which tells the decision maker to discard components from the evaluation that are shared by all prospects. The *cancellation* operation may be considered a process heuristic in design because it guides the decision-making process, rather than selecting the details of an artifact.

When comparing the use of heuristics to the current idea of "rational" decision making, process heuristics should be included in the discussion. In normative decision-making, the rational designer makes decisions that maximize the expected value of the design. Lee and Paredis showed that value maximization must consider not only the outcome resulting from the use or sale of the artifact, but must also consider the cost of the resources needed to execute the corresponding design process in an organizational context [18]. Binder also discussed how heuristics outside of artifact heuristics affect the value of a product [13]. If it is desired to understand when to use heuristics in a way that maximizes the expected utility of design, it is beneficial to study process heuristics applied by designers in complex systems design.

Maier [19] described heuristics as lessons learned from one's previous experiences, as well as the experiences of others, that serve as a complement to analytical processes. In systems architecting, the creation, and building of systems, the architecting role is presented as more typically reliant on heuristics over analytics. Each architect must use their own tool kit of heuristics with careful judgment, as no two systems they encounter will be the same. From a systems perspective, Maier [19] found value in many different characteristics of heuristics, such as reducing complexity, applying outside their original context, and connecting to a portion of the design process. An example heuristic presented by Maier [19] is "In partitioning, choose the elements so that they are as independent as possible; that is, choose elements with low external complexity and high internal complexity." Additionally, from an organizational perspective, process heuristics can improve problem formulation and analysis by identifying and preventing issues, such as Type III errors [20], [21].

This article aims to contribute to the theory of process heuristics and the methodology for obtaining them from designers, employing the contextual application of complex systems design. There are improvements to be made in the methodology such that adequate information is extracted for future validation and application of heuristics. There is new insight into characteristics of process heuristics based on how they are presented by the designers. This article will be the basis for future work by the authors, creating a repository of heuristics that enhances the heuristic competence of the designer. It will address what information is needed to have a sufficient repository and what changes should be made in the methodology to obtain this new information.

Von der Weth and Frankenberger [22] stressed the need for heuristic competence in design because it gives designers confidence to attack novel problems. They defined heuristic competence as having possession of a pool of heuristic knowledge and the ability to appropriately apply that knowledge for problem solving. On the other side, less heuristically competent people may avoid new situations because of previous failures with heuristics. Maier similarly believed that "knowing when and how to use a heuristic is as important as knowing what and why [19]." The authors of this article envision developing a mental pool of knowledge into a documented repository with which designers can appropriately apply heuristics when valid and increase their competence with heuristics in design. The authors performed a case study of designers at the Jet Propulsion Laboratory (JPL) to understand how to target process heuristics within the context of complex system design during extraction and what factors and information should be considered when developing this repository.

II. Methods

A. Heuristic Analysis Through Case Studies

This article used a mixed-method case study of interviews and document analysis to extract heuristics from designers at JPL. The research methods chosen to study heuristics will factor into how accurately heuristics and the environments in which they are used can be portrayed. This section gives an overview of how case studies have been previously used to study heuristics, along with factors to consider when using those methods.

Case studies investigate a *case* (individual or group) to answer research questions by extracting and combining a range of evidence within the case setting [23]. One key attribute of case studies is the ability to collect data using multiple methods: interviews, observations, document analysis, etc. The researcher then works *inductively* to develop theory that is grounded in evidence in the data. The qualitative data are often analyzed through *coding*, a process for discovering patterns in the data to be used for additional analysis [24]. One typical concern about case studies is their ability to be generalized. Creswell [25] described the case study as a "bounded system"—meaning the results are bounded by a particular time and place. However, Yin [26] argued that case studies, just like controlled experiments, are meant to expand and generalize theories over time.

It is easy to confuse case studies with other methods, such as an ethnography. In an ethnography, the researcher is engaged with the daily activity of the subjects as a participant-observer for long periods of time [25]. The goal is to describe and interpret these activities rather than to develop theory. Both methods require a more natural setting than a controlled experiment. Ethnographies have an intense study duration, lack of prior theory or hypotheses, and emphasis on observational evidence that separate them from case studies [26]. Ball and Ormerod [27] addressed the complications of implementing ethnography into design research. For example, it is often difficult to gain access into a designer's natural work environment for extensive periods of time as a participant-observer. Design studies also tend to have applied goals that aim to improve the design process, contrary to true ethnographies meant to simply describe but not modify the environment of focus.

Many studies of heuristics do not refer to themselves as case studies or any other type of study. Many of them can be assumed to be case studies by the method of data collection and the targeting of a specific group. For example, Yilmaz *et al.* [29] focused their study specifically on products considered to be "innovative," whereas Bingham *et al* [28]. interviewed only corporate executives in entrepreneurial firms. Previous case studies of heuristics have been broken into four main modes of data collection:

1) artifact analysis,
2) document analysis,
3) interviews,
4) surveys.

1) Artifact Analysis: Overall, most case studies in design have relied on artifact analysis to infer how a designer uses heuristics to reach a final product [29]–[38]. An artifact is defined here as any tangible object produced by humans or nature [39]. An artifact can be physically present or represented by sketches, photos, etc. The literature presented here contains a mix of studies that examined concept sketches, patents, and finished products.

The product analysis method used by Yilmaz *et al.* [29] begins with identifying a set of products to be studied. Heuristics are extracted by hypothesizing actions that led to identified features and elements. The reliability of these heuristics is presented through an interrater process of multiple coders. It is not meant to say these heuristics are the exact processes taken by each designer, but rather that it is possible to use the heuristics to reach similar results. The process used by Yilmaz *et al* [29]. is similar to other studies identifying heuristics by patents or product analysis, although there are some variations. To identify environmentally conscious guidelines, Telenko and Seepersad [30] added a life cycle analysis to existing products. Singh added a "deductive approach" by hypothesizing new situations in which design transformation is necessary, and for which heuristics can facilitate that innovation [31]. In each study, there is one clear theme—using a final product to hypothesize intermediate actions. Only one study identified obtained a sequence of sketches from an expert in industrial design, making it easier to see the designer's transitions from one idea to the next. [32].

TABLE I
ADVANTAGES AND DISADVANTAGES FOR INTERVIEW AND SURVEYS [45]

Method	Advantages	Disadvantages
Interviews	• Participants can describe events in full detail • Interviewer can guide conversation and control the information received	• Participants describing what they believe the researcher wants to hear, instead of reality • Obtaining clear, articulate responses • Responses filtered through researcher's eyes
Surveys	• Relatively inexpensive form of data collection • Reaches diverse population within short period	• May confirm what people think and not necessarily what they do • Blind to outside variables that contribute to correlations found in the survey data

Some studies are now turning to computer-based models for assistance with extracting or evaluating heuristics from artifacts. McComb *et al*. [33] used hidden Markov models to identify heuristics through intermediate design actions. A hidden Markov model is a two-stage stochastic process, which first describes state transitions within a discrete and finite state space, then generates outputs for every point in time [40]. The "hidden" descriptor is attached because the sequence of outputs is the only observable piece of the model's behavior. Matthews *et al.* [34] also took a computational approach to recognize patterns in existing solutions. A verification stage uses experts to judge the accuracy, novelty, and importance of each heuristic per their own beliefs. Both models attempt to find the intermediate steps of a known final artifact. Binder, however, creates simulated artifacts and compares two different approaches for designing a pressure vessel: a heuristic approach and an optimization-based, expected-utility maximization approach [35].

2) Document Analysis: Identifying heuristics through document analysis is a method found in multiple studies [41]–[44]. For each document, a coding process is used to find patterns in the data, and these patterns become represented as heuristics for a domain. For example, Reap and Bras [41] studied prior literature to present guidelines for environmentally benign design and manufacturing. Concepts coded were grouped into categories. The set of categories considered to be principles was reduced using criteria, such as "strong presence in literature" or "foundational importance in biology and ecology." The literature was then revisited to turn the phrases into descriptive principles.

Many studies describe their own reasons for not implementing analysis of literature or similar records. Telenko and Seepersad [30] decided against a literature analysis for environmentally conscious guidelines due to the risk of unforeseen tradeoffs and the possibility that they may not be applicable to current environmental issues. Additionally, Bingham *et al*. [28] believed document analysis lacks the insight into organizational processes necessary to fully describe a heuristic.

3) Interviews and Surveys: Methods, such as interviews and surveys, may corroborate heuristics directly with the study participants. Table I gives an overview of some common advantages and disadvantages of the two methods according to Creswell [45]. Studies using interviews to examine heuristics typically followed the "semistructured" format using an initial predetermined set of questions, with room for follow-up questions throughout the interview [16], [28], [46], [47]. Heuristics were extracted by transcribing audio and coding the interview similar to the document analysis technique. One unique contribution from Bingham *et al.* [28] related the use of process heuristics to better performance in organizational processes, although they did not present a full set of extracted heuristics.

Surveys mostly use closed-ended questions in which participants choose among a given set of responses. Open-ended questions do not constrain responses, but they do require coding the data for themes as part of the analysis. Many surveys combine both methods by giving participants a set of responses, along with the option to write-in an alternative response if the given responses are not sufficient. Only one study was found to use surveys as a primary method for extraction and verification of heuristics by using the Delphi method [48]. Experts were sent a predetermined set of heuristics and asked to rate the heuristic according to its relevance in computer-supported collaborative work. The survey gave the option of adding new heuristics to the set as well. There were three rounds of surveys, with the surveys edited based on previous ratings and additions. The end product was a set of heuristics meeting the threshold of relevance for collaborative creativity.

Most of the papers in this literature review came from engineering- or design-based research, but there are other domains, such as management, that are present as well. For example, although process heuristics have an impact on design, the studies cited that focus specifically on process heuristics provide a management perspective through the use of interviews [16], [28]. The reliance on interviews is potentially due to a lack of physical artifacts present outside of a design context, as well as the inability of archived documents to provide an adequate view of the context. In this article, interviews have been paired with artifacts derived from a workshop with participants to study the use of process heuristics within a complex systems design team.

B. Experimental Procedure

Based on the definitions presented by Gillham and Yin, this article is a case study of complex system design experts at the JPL using a mixed-method approach of interviews and artifact analysis [23], [26]. This article documents process heuristics through a focus group interview lasting 30 min and was part of a larger sequence of studies to develop a repository of heuristics for a group of designers at the JPL. The group interview took place within a workshop developed to present the authors' current progress on heuristics research at JPL, followed by the designers discussing various aspects of their own heuristics and how cataloging this information may be valuable to them. This method gave the researchers the ability to facilitate interaction and discussion with the participants, while ensuring they understood heuristics and had the ability to see heuristics in their own work. The participants in the workshop are all designers within one specific group at JPL's Innovation Foundry known as the Architecture Team (A-Team). The artifact analyzed from this study is an affinity diagram of process heuristics used within the A-Team. The study concludes with a second interview process with two A-Team leaders, conducted postworkshop. Studying this population of mission designers can be considered analogous to other complex systems design teams, although this study could be performed with designers of any group in any domain of engineering.

Before performing this study, the researchers received IRB approval at their institution to perform the human subjects study as designed. Then, participants were recruited to the study by email, and those that agreed to participate signed a consent form before the study began. The study took place at JPL in the same room used to conduct A-Team studies, known as Left Field. Left Field is favored for its large whiteboard space, configurability, and comfort. This location gave participants a comfortable, familiar environment during the study. More information on the A-Team and their work can be found in. [49].

In total, eight members of the A-Team participated in the study. Two participants had participated in a previous study with the research team, and the remaining members had no prior affiliation with the research team before the workshop. There was no compensation for participation. The workshop began with a 30-min presentation to participants to deepen their understanding of heuristics. This presentation began by defining heuristics and the motivation for studying them. Then, heuristics collected in a prior study with the A-Team were shown, along with a preliminary analysis of those heuristics [14]. At the end of the presentation, the focus group interview began. The participants spent 30 min going through the following discussion questions.

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

After 30 min, the workshop then turned toward individual brainstorming of heuristics. Participants were instructed to focus specifically on process heuristics that guide the design process, rather than the design choices for details of an artifact. An example given as a process heuristic used in A-Team studies was "When designing an A-Team study, split the requirements, problems, and solutions into three different brainstorming processes." Each participant was given 10 min to write down as many process heuristics as they could think of that are used during A-Team studies, using the sticky notes provided. The sticky notes method is the A-Team's typical method of brainwriting, so this activity was something each participant was familiar

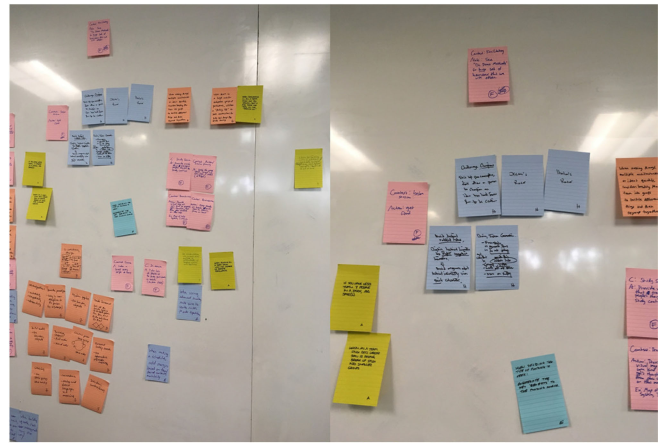

Fig. 1. Examples of sticky notes containing heuristics placed on the board.

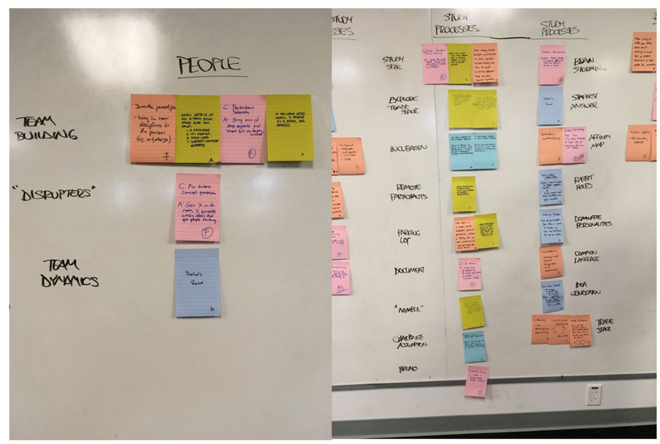

Fig. 2. Example of heuristics grouped into categories during affinity mapping.

with and comfortable with performing. They were encouraged to write these heuristics in context-action form, although heuristics were not rejected if they could not do this in the allotted time [14]. After the 10-min elapsed, all members placed their own sticky notes on the floor-to-ceiling whiteboard wall and attempted to categorize the heuristics on the board, similar to how they would in a typical A-Team study. This process is often called affinity diagramming in design [50]. Figs. 1 and 2 show some of the sticky notes on the whiteboard and the attempt to group the heuristics.

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

After this process, the researchers interviewed both A-Team leaders individually for more insight into the heuristic categories and contexts surrounding the extracted process heuristics. These interviews were in-person at JPL and lasted about 1 h each. These interviews were not intended to extract additional process

TABLE II
NUMBER OF HEURISTICS GENERATED PER PARTICIPANT

Participant	No. Heuristics
A	6
B	4
D	4
E	4
F	12
G	5
H	5
J	10

TABLE III
SAMPLE OF PROCESS HEURISTICS GENERATED

Primary Category	Process Heuristic
People	If you have less than 7 people in a study, add SME (s).
Pre-Study Processes	For study planning, start with an agenda from a study that went well, then modify it.
Study Processes	When using technical heuristics, pause mid-study and ask: what if we rejected (replaced) a central assumption?
Tools	For trade studies, use science value metrics to differentiate and compare mission architectures.
Resources	For the study session, provide visuals that transport people's thought to study context.

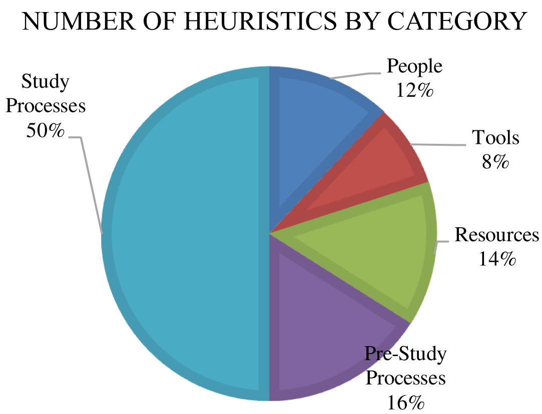

Fig. 3. Percentage of heuristics per primary category ($n = 50$).

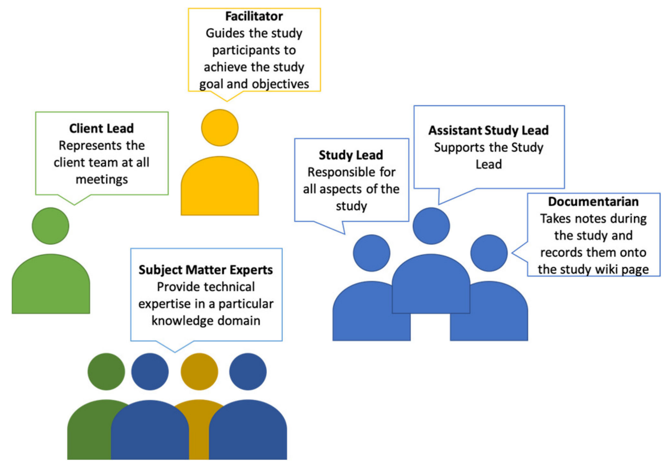

Fig. 4. Typical A-Team study setup.

heuristics, but to understand more about the environment in which the current set of heuristics was being used. To generate interview questions, researchers collectively studied the heuristics and hypothesized additional information about the A-Team, which may be missing. The information gathered from these interviews is discussed throughout Section IV for each primary heuristic category.

Data were collected during all interviews and the affinity mapping process by recording all audio, then transcribing the recordings afterward for analysis. Artifacts collected during heuristic generation included the physical sticky notes containing the heuristics. The affinity map containing heuristics and heuristic categories was documented through photos of heuristics on the floor-to-ceiling whiteboard wall in their respective groups.

III. RESULTS

From the eight participants, 50 heuristics were produced from the study over a 10-min brainwriting period. The average number of heuristics per participant was 6.25 heuristics, with the highest individual total being 12 heuristics and the lowest being 4 heuristics. The number of process heuristics generated per participant is shown in Table II. The categorization performed after affinity mapping led to five main categories: people, tools, resources, prestudy processes, and study processes. Study process is the largest category with 50% of the heuristics, and the other four categories contain the remaining 50%. The breakdown of heuristics by category is shown in Fig. 3. Example heuristics from each primary category can be found in Table III.

IV. ANALYSIS AND DISCUSSION

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

A. A-Team Heuristic Category: People

Fig. 4 presents an overview of the people typically present in an A-Team study. The A-Team prefers 12–15 participants in each study so that different strengths will overlap and lead to an answer/solution. People in an A-Team study can be split into three main groups: the client team, the A-Team (study lead, assistant study lead, facilitator, and documentarian), and the subject matter experts (SMEs).

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

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

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

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

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

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

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

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

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

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

B. A-Team Heuristic Category: Prestudy Processes

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

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

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

2) Planning Meeting: An additional meeting called the "planning meeting" will check on the progress of recruiting participants and making sure that there are enough people to have a successful A-Team study. The planning meeting is two weeks before the day of the A-Team study, and a second meeting one week before the A-Team study may be necessary if new

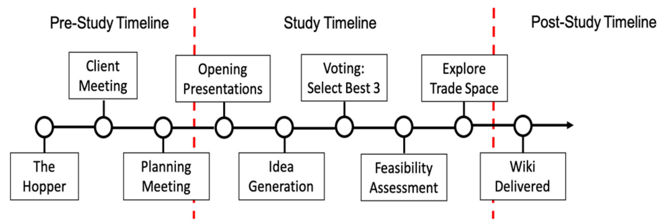

Fig. 5. Example A-Team study timeline.

information is obtained or other details have changed. The reasoning behind the length of time set aside to plan an A-Team study is more about getting a time that works for the desired participants. The farther out it is planned, the easier it is to get on everyone's calendar.

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

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

C. A-Team Heuristic Category: Study Processes

A-Team studies focus on three main levels of concept maturity: idea generation, feasibility assessment, and trade space exploration, as shown in Fig. 5. The study processes will follow the agenda created by the study lead, through collaboration with the facilitator and the client. The heuristics for study processes mostly include guidelines that the facilitator may employ during the study. Due to a lack of standard training of facilitators outside of experience running studies, a repository of heuristics for facilitators would benefit the onboarding of new members of the A-team, especially in the facilitator role.

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

Participant D: "An example of how it (the heuristic) evolves. We used to write your idea down on a sticky note … Somebody stands up, reads their sticky notes and puts them on the board. Then we organize it. We usually do it, we still do it. But then, one time we did a study where we instead had people stand at the board and write on their sticky notes while we were up there. We

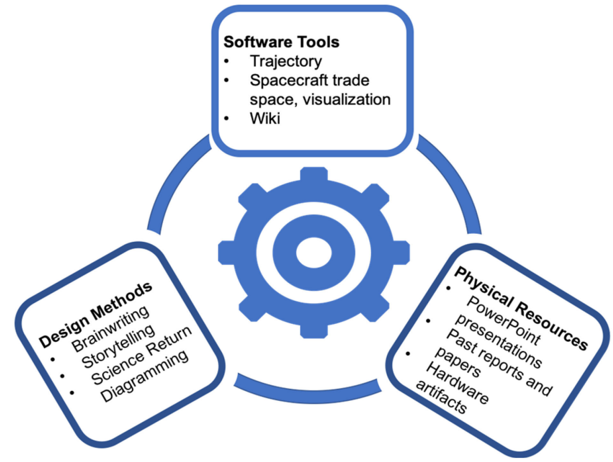

Fig. 6. Overview of A-Team tools and resources.

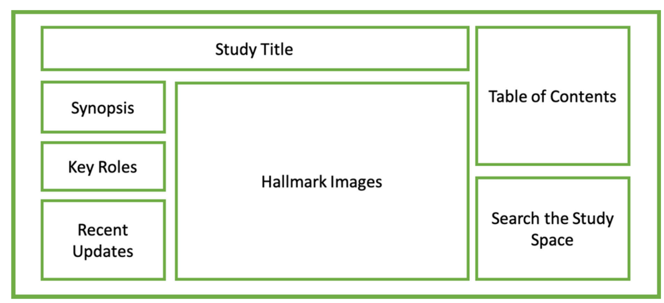

Fig. 7. Example outline of Wiki content.

got a different outcome. The benefit was we didn't get as many repetitions because we could see things and build off each other more quickly. The other side is people were way more biased, so there is an upside/downside. I actually think I prefer the second one where we all stand at the board."

D. A-Team Heuristic Category: Tools + Resources

1) Software Tools: Fig. 6 lists the tools and resources commonly used by the A-Team. The software tools category is specifically for more software-oriented tools that assist the A-Team during a study. For example, the Hopper wiki, described earlier, is a tool that organizes potential future studies. The wiki is divided up into A-Team Core and A-Team Studies. A-Team Studies are divided into Client Notes, Hopper, Planning, In Session, and Completed. The contents of the In-Session wiki is passed on as a final product to the client, as well as stored by the A-Team as a reference for future studies. All study participants have access to the wiki after the study. Once the study is complete, the wiki is cleaned up, and the study lead ensures that everything the client requested is contained in the wiki. This is the usual final product delivered to the client and documents the study for future usage. Figs. 7 and 8 show example of wiki page outlines shared with participants.

2) Physical Resources: An introduction package distributed at the beginning of a study contains the study goals and objectives from the client meeting notes, a list of desired participants, and an overview of who the A-Team is and what they do. This

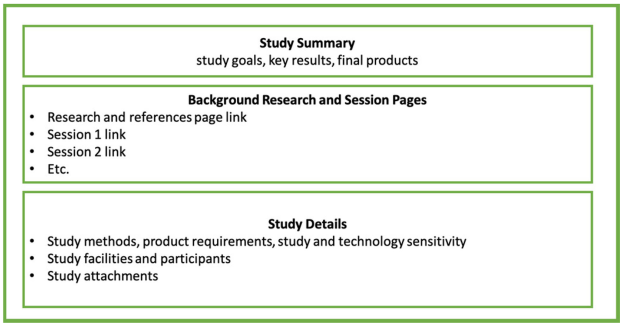

Fig. 8. Example outline of Wiki content.

keeps members on the same page for the study without having to restate basic information throughout the meeting. It also helps participants who are new to the A-Team understand the full potential of the A-Team; people will often only know about one specific thing the A-Team does and not the full range of study types and tools. Information from client notes and the intro package are placed in the wiki, along with everything documented during the study.

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

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

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

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

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

The first two concerns lead directly into the third factor—how much information should be included in an articulation of a heuristic? The amount of information will correlate with the detail with which the heuristics are extracted. The level of granularity and supplemental information will affect the categorization, as well as the ability to determine its relevance to the design problem [3]. Ultimately, a designer should have enough information to determine whether the heuristic should be used in the current design context.

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

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

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

E. A-Team Process Heuristics

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

The heuristics captured tend to require application externally to the entire A-team, instead of an individual's inner mental processes. An example of an inner process is "When facilitating, use the de Bono Methods." The de Bono method is something the facilitator consciously keeps in mind during the study, but it is not something explicitly followed by the rest of the study team [51]. On the other hand, the heuristic "For trade studies, use science value metrics to differentiate and compare mission architectures" would be carried out explicitly by the entire team. The heuristics also tend to apply to either the facilitator or the study lead, when compared with other members, such as the client lead, documentarian, or SMEs. These characteristics have an impact on the repository when considering its targeted user. The study lead may struggle with navigating a repository with too many heuristics that are not applicable to their role on the team. On the other hand, the study lead may have a more accurate mental model of the study to be performed if they are fully aware of the heuristics that each facilitator brings to the study. This awareness of other heuristics in the design space may bring its own impact to the decision-making process.

The heuristics captured appear to be mostly informal processes, rather than formal design methods commonly found in literature. For example, a formal process heuristic for idea generation would be "brainstorming," and an informal method would be "If you have less than seven people in a study, add SMEs." Processes were considered formal if the heuristic was listed as a named or titled process, such as the "de Bono" methods or the "double diamond" design process [52]. Of the six heuristics labeled as formal processes, five of them were categorized as in-study processes. It is hypothesized that the formal process heuristics originated through sources outside of an A-Team study, whereas informal methods were more likely to be developed and refined through experiences within the A-Team studies. This would imply that the designers are relying mostly on experience alone for planning studies and getting the right people, tools, and resources in the room. From a value perspective, it is possible that the designer may place higher value on heuristics developed from their own experiences compared with those from outside sources, or that the designers may not be aware of external heuristics that could potentially add value to the process. These hypotheses will be tested in future studies that document how the heuristics originated and more accurately assess the value designers place on heuristics.

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

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

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

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

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

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

F. Analysis of Methodological Outcomes

One benefit of the method used in this study was ensuring a proper comfort level for the participants. The location of the study, the collection of participants, and the agenda of the study (presentation, discussion, brainwriting) made it similar to previous A-Team studies, which may have made them more willing to speak and be engaged. Providing examples of heuristics used within their team from a previous study may have helped improve the understanding of heuristics or at least have helped participants see where the heuristics are applicable in their own work. The presentation and discussion before the heuristics generation helped designers see the need for understanding their own heuristics and may have motivated them during the generation phase. The ability for this method to translate to teams who may not be as experienced with brainwriting and affinity mapping should be explored, as this may be a potential limitation of the method.

This study allowed the A-Team members to group the heuristics on their own, as opposed to having an outsider group them. This may help the A-Team implement the heuristic repository into their current processes, but it does not necessarily mean that this is the best way to categorize the heuristics. Therefore, this could also be a limitation. This same idea applies to the verification of the heuristics. It is beneficial that the heuristics have been self-validated, but a more robust validation will confirm these heuristics through triangulation using additional methods, such as observations or additional artifact analysis from within A-Team studies.

Further limitations may include biased results based on the heuristics that the research team showed them during the presentation, causing an effect such as design fixation [53]. Additionally, the mixture of various experience and leadership levels in the study may have created pressure/influence during heuristic generation. Some participants may have felt uncomfortable articulating a heuristic that may have surprised higher management or be refuted by other participants. However, the A-Team does its best to limit that type of hierarchical culture, because all studies tend to have a diverse set of people in the room.

It is hard to say when the list of heuristics is saturated or has become robust. There is no limit on the number of heuristics that may be used, and it would take many additional studies to ensure the list is exhaustive. To this end, there may be additional properties of process heuristics left undiscovered, and trends may evolve as new heuristics are discovered and analyzed.

Future work may include an additional round of heuristic generation to fill in the gaps based on the categories.

V. Conclusion

This article presents a unique case study using interviews and artifact analysis surrounding a 2-h workshop with the A-Team at the JPL. The interviews gave insight into the role of heuristics within a complex system design team and how documenting them can be valuable. Within the A-Team specifically, there is a need for documenting the process heuristics for planning and facilitating an A-Team study. This case study resulted in an initial extraction of process heuristics currently used to handle these aspects of a study.

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

Acknowledgment

The authors would like to thank Dr. Randii Wessen for his contributions to this article. The authors would also like to thank the members and leadership of the A-Team for their participation in this study. This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology.

References

[1] K.-E. Warneryd, "The economic psychology of the stock market," in *The Cambridge Handbook of Psychology and Economic Behaviour*, A. Lewis, Ed. Cambridge, U.K.: Cambridge Univ. Press, 2008.

[2] B. V. Koen, *Definition of the Engineering Method*. Washington, DC, USA: Amer. Soc. Eng. Educ., 1985.

[3] K. K. Fu, M. C. Yang, and K. L. Wood, "Design principles: Literature review, analysis, and future directions," *J. Mech. Des.*, vol. 138, 2016, Art. no. 101103.

[4] J. v. Neumann and O. Morgenstern, *Theory of Games and Economic Behavior, 60 Anniversary Commemorative Edition* (Princeton Class Editions). Princeton, NJ, USA: Princeton Univ. Press, 2004.

[5] J. Fox, "From "economic man" to behavioral economics," *Harvard Bus. Rev.*, vol. 93, no. 5, pp. 78–85, 2015.

[6] M. Friedman and L. J. Savage, "The utility analysis of choices involving risk," *J. Political Econ.*, vol. 56, no. 4, pp. 279–304, 1948.

[7] A. Tversky and D. Kahneman, "Judgement under uncertainty: Heuristics and biases," *Science*, vol. 185, no. 4157, pp. 1124–1131, 1974.

[8] D. Kahneman, *Thinking, Fast and Slow*, 1st ed. New York, NY, USA: Farrar, Straus and Giroux, 2013.

[9] M. G. Haselton, D. Nettle, and D. R. Murray, "The evolution of cognitive bias," in *Handbook of Evolutionary Psychology*. Hoboken, NJ, USA: Wiley, 2016.

[10] A. W. Lo, "Survival of the richest," *Harvard Bus. Rev.*, vol. 84, no. 3, pp. 20–22, 2009.

[11] G. Gigerenzer, "Why heuristics work," *Perspectives Psychological Sci.*, vol. 3, no. 1, pp. 20–29, 2008.

[12] G. Gigerenzer, "On narrow norms and vague heuristics: A reply to Kahneman and Tversky" *Psychological Rev.*, vol. 103, no. 3, pp. 592–596, 1996.

[13] W. R. Binder, "A method for comparing heuristics with applications in computational design of flexible systems" Ph.D. Thesis, George W. Woodruff School Mech. Eng., Georgia Inst. Technol., Atlanta, GA, USA, 2017.

[14] K. B. Fillingim, R. O. Nwaeri, F. Borja, K. Fu, and C. J. J. Paredis, "Design heuristics: Analysis and synthesis from Jet Propulsion Lab's architecture team " presented at the ASME 2018 Int. Des. Techn. Conf. Comput. Inf. Eng. Conf., 2018.

[15] S. Yilmaz, S. R. Daly, C. M. Seifert, and R. Gonzalez, "A comparison of cognitive heuristics use between engineers and industrial designers," presented at the 4th Int. Conf. Des. Comput. Cognit., Stuttgart, Germany, July 12–14, 2010.

[16] D. W. Barclay and M. D. Bunn, "Process heuristics in organizational buying: Starting to fill a gap" *J. Bus. Res.*, vol. 59, pp. 186–194, 2006.

[17] D. Kahneman and A. Tversky, "Prospect theory: An analysis of decision under risk," *Econometrica*, vol. 47, no. 2, pp. 263–291, 1979.

[18] B. D. Lee and C. J. J. Paredis, "A conceptual framework for value-driven design and systems engineering," *Procedia CIRP*, vol. 21, pp. 10–17, 2014.

[19] M. W. Maier, *The Art of Systems Architecting*, 3rd ed. Boca Raton, FL, USA: CRC Press, 2009.

[20] P. F. Katina, "Emerging systems theory-based pathologies for governance of complex systems," *Int. J. Syst. Eng.*, vol. 6, no. 1/2, pp. 144–159, 2015.

[21] K. M. Adams and P. T. Hester, "Errors in systems approaches," *Int. J. Syst. Eng.*, vol. 3, no. 3/4, pp. 233–242, 2012.

[22] R. Von der Weth and E. Frankenberger, "Strategies, competence, and style—Problem solving in engineering design," *Learn. Instruction*, vol. 5, pp. 357–383, 1995.

[23] B. Gillham, *Case Study Research Methods*, 1st ed. (Continuum Research Methods Series). London, U.K.: Bloomsbury Publ. PLC, 2000.

[24] J. Saldana, *Fundamentals of Qualitative Research*. London, U.K.: Oxford Univ. Press, 2011.

[25] J. W. Creswell, *Qualitative Inquiry and Research Design: Choosing Among Five Traditions*. Thousand Oaks, CA, USA: Sage Publ., 1998.

[26] R. K. Yin, *Case Study Research Design and Methods*, 2nd ed. (Applied Social Research Methods Series). Thousand Oaks, CA, USA: Sage Publ., 1994.

[27] L. Ball and T. C. Ormerod, "Applying ethnography in the analysis and support of expertise in engineering design," *Des. Stud.*, vol. 21, no. 4, pp. 403–421, 2000.

[28] C. B. Bingham, K. M. Eisenhardt, and N. R. Furr, "What makes a process a capability? Heuristics, strategy, and effective capture of opportunities," *Strategic Entrepreneurship J.* vol. 1, pp. 27–47, 2007.

[29] S. Yilmaz, C. Seifert, S. R. Daly, and R. Gonzalez, "Design heuristics in innovative products," *J. Mech. Des.*, vol. 138, no. 7, 2016, Art. no. 071102.

[30] C. Telenko and C. C. Seepersad, "A methodology for identifying environmentally conscious guidelines for product design," *J. Mech. Des.*, vol. 132, pp. 1–9, Sep. 2010.

[31] V. Singh, S. M. Skiles, J. E. Krager, and K. L. Wood, "Innovations in design through transformations: A fundamental study of transformation principles," in *Proc. ASME Int. Des. Eng. Techn. Conf. Comput. Inf. Eng. Conf.*, Philadelphia, PA, USA, 2006, pp. 1–14.

[32] S. Yilmaz and C. M. Seifert, "Creativity through design heuristics: a case study of expert product design," *Des. Stud.*, vol. 32, no. 4, pp. 384–415, 2011.

[33] C. McComb, J. Cagan, and K. Kotovsky, "Mining process heuristics from designer action data via hidden Markov models," *J. Mech. Des.*, vol. 139, no. 11, 2017.

[34] P. C. Matthews, L. T. M. Blessing, and K. M. Wallace, "The introduction of a design heuristics extraction method," *Adv. Eng. Informat.*, vol. 16, pp. 3–19, 2002.

[35] W. R. Binder and C. J. J. Paredis, "Optimization under uncertainty versus algebraic heuristics: A research method for comparing computational design methods," in *Proc. ASME Int. Des. Eng. Tech. Conf. Comput. Inf. Eng. Conf.*, 2017, doi: 10.1115/DETC2017-68371.

[36] R. B. Stone, K. L. Wood, and R. H. Crawford, "A heuristic method for identifying modules for product architectures," *Des. Stud.*, vol. 21, pp. 5–31, 2000.

[37] R. D. Campbell, P. K. Lewis, and C. A. Mattson, "A method for identifying design principles for the developing world," in *Proc. ASME Int. Des. Eng. Techn. Conf. Comput. Inf. Eng. Conf.*, Washington, DC, USA, 2011, pp. 1–8.

[38] *Research and Practice on the Theory of Inventive Problem Solving (TRIZ)*. Basel, Switzerland: Springer, 2016.

[39] G. R. Gibbs, *Analyzing Qualitative Data*. Newbury Park, CA, USA: Sage, 2018.

[40] G. A. Fink, *Markov Models for Pattern Recognition: From Theory to Applications*, 2 ed. Berlin, Germany: Springer, 2014.

[41] J. Reap and B. Bras, "A method of finding biologically inspired guidelines for environmentally benign design and manufacturing," *J. Mech. Des.*, vol. 136, pp. 1–11, Nov. 2014.

[42] C. Antoun, J. Katz, J. Argueta, and L. Wang, "Design heuristics for effective smartphone questionnaires," *Soc. Sci. Comput. Rev.*, vol. 36, no. 5, pp. 557–574, 2018.

[43] H. A. Reijers and S. L. Mansar, "Best practices in business process redesign: An overview and qualitative evaluation of successful redesign heuristics," *Int. J. Manage. Sci.*, vol. 33, pp. 283–306, 2005.

[44] C. Telenko, J. M. O'Rourke, C. C. Seepersad, and M. E. Webber, "A compilation of design for environment guidelines," *J. Mech. Des.*, vol. 138, pp. 1–11, Mar. 2016.

[45] J. W. Creswell, *Educational Research: Planning, Conducting, and Evaluating Quantitative and Qualitative Research*, 4th ed. Boston, MA, USA: Pearson Edu., Inc., 2012.

[46] R. T. Harrison, C. Mason, and D. Smith, "Heuristics, learning and the business angel investment decision-making process," *Entrepreneurship Regional Develop.*, vol. 27, no. 9/10, pp. 527–554, 2015.

[47] T. Herrmann, "Design heuristics for computer supported collaborative creativity," presented at the 42nd Hawaii Int. Conf. Syst. Sci., 2009.

[48] C. S. York and P. A. Ertmer, "Towards an understanding of instructional design heuristics: An exploratory Delphi study," *Educ. Technol. Res. Develop.*, vol. 59, no. 6, pp. 841–863, 2011.

[49] J. K. Ziemer, R. R. Wessen, and P. V. Johnson, "Exploring the science trade space with the JPL innovation foundry A-Team," presented at the SESCA, Madrid, Spain, 2016.

[50] B. Harrington and B. Martin, *Universal Methods of Design: 100 Ways to Research Complex Problems, Develop Innovative Ideas and Design Effective Solutions*. Gloucester, MA, USA: Quayside Publ. Group, 2012.

[51] E. D. Bono, *Lateral Thinking: A Textbook of Creativity*. Baltimore, MD, USA: Penguin, 2009.

[52] P. R. N. Childs, *Mechanical Design Engineering Handbook*. Burlington, NJ, USA: Elsevier Sci., 2013.

[53] J. S. Linsey, I. Tseng, K. Fu, J. Cagan, K. L. Wood, and C. Schunn, "A study of design fixation, its mitigation and perception in engineering design faculty," *J. Mech. Des.*, vol. 132, no. 4, 2010, Art. no. 041003.

Kenton B. Fillingim received the B.S. degree in mechanical engineering from the University of South Alabama, in 2016, and the M.S. degree in mechanical engineering in 2018 from Georgia Institute of Technology, Atlanta, GA, USA, where he is currently working toward the Ph.D. degree in mechanical engineering.

He is a Graduate Research Assistant with Georgia Tech. His research interest includes understanding the use of approximations and heuristics in systems engineering and design.

Hannah Shapiro received the B.S. degree in mechanical engineering while minoring in industrial design from the Georgia Institute of Technology, Atlanta, GA, USA.

She is an Undergraduate Research Assistant with the Georgia Institute of Technology. She is currently working to study how computational supports for design by analogy practice enhances the development of effective and innovative concept development. Her research interests include engineering design and early concept development.

Christiaan J. J. Paredis received the B.S. and M.S. degrees in mechanical engineering from Katholieke Universiteit Leuven, Leuven, Belgium, in 1988, and the M.S. and Ph.D. degrees in electrical and computer engineering from Carnegie Mellon University, Pittsburgh, PA, USA, in 1990 and 1996, respectively.

He joined the Automotive Engineering Faculty as the BMW Endowed Chair in Systems Integration in January 2018. Previously, he was with the Mechanical Engineering Faculty, Georgia Tech, as the Program Director at NSF in Systems Engineering and Design, and as a Research Scientist with Carnegie Mellon. His research work combines the aspects of decision theory, information technology, simulation, and systems theory to support the design of complex engineered systems.

Katherine Fu received her B.S. degree in mechanical engineering from Brown University, Providence, RI, USA, in 2007 and the M.S. and Ph.D. degrees in mechanical engineering from Carnegie Mellon University, Pittsburgh, PA, USA, in 2012 and 2009, respectively.

She is an Assistant Professor of mechanical engineering with the Georgia Institute of Technology. She was a Postdoctoral with MIT and SUTD. Her research interests include studying engineering design through cognitive studies and extending those findings to the development of methods and tools to facilitate more effective, inspired design, and innovation.