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DESIGN HEURISTICS: ANALYSIS AND SYNTHESIS FROM JET PROPULSION LABORATORY'S ARCHITECTURE TEAM

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ABSTRACT

This study offers insight into the processes of expert designers at the Jet Propulsion Laboratory (JPL) and how they make use of 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. 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 analyzed to show correlations between the participant perceptions of frequency of use, reliability, and evolution of a heuristic. 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.

1. INTRODUCTION

Heuristics are rules of thumb providing guidance for choosing the next design action, given the current state of the design process. 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 then prescribing how heuristics should be used. Being able to justify the use of one heuristic over another will lead to more efficient 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 rigorous 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. 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 questions: How do expert designers use design heuristics? What is a repeatable method for extracting valid heuristics from designers? How can heuristics be characterized and classified?

2. RELATED WORK

2.1 Framework for Heuristics

At a fundamental level, engineering design can be thought of as a decision-making process [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 artefact-focused, process-focused, and organization-focused perspective [1]. From the artefact-focused perspective, the designer aims to choose, from the set of all possible artefacts, the artefact that maximizes value. From the process-focused perspective, the designer also considers the time and cost associated with the process for finding such an artefact. 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 this point is never crossed, designers resort to heuristics. Gigerenzer describes heuristics as "fast and frugal" decisions using a minimum of time,

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knowledge, and computation [2]. 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) [3].

The ability of heuristics to produce satisfactory results depends on how well they allow decision makers to adapt to their current environment. From the artefact-focused perspective, heuristics allow the designer to constrain the number of alternatives considered [1]. 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 [4]. 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 value. When taking the cost of the maximization into account, 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 value [1]. 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 [1]. 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 [5].

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 value [6]. From this value-driven design (VDD) perspective, there are no requirements placed on the system, product, or component attributes [7], 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 [8]. 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 [9]:

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 [9]. 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 [5]). 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 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 Heuristic Extraction Methods

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 [9]. 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.

A series of studies performed by Daly and Yilmaz [10-16] significantly contributes to current heuristic extraction methods. Their methodology relies on protocol studies where participants think aloud while generating design solutions [10-13]. 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 [11]. Hypothesized actions potentially leading to these characteristics were considered heuristics and generalized for applicability outside the initial context [12]. 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 [13]. As studies progressed, coders used heuristics from previous studies as a starting point and added new heuristics to the set as necessary [10]. 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 [14]. 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 extracted heuristics by hypothesizing about the actions taken by designers that led to features identified in innovative products [15]. Rather than searching across multiple sketches for key features, products were analyzed individually, 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 [17]. 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 [18].

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 (CMEA) to identify characteristics affecting consumer product flexibility [19]. Then, potential guidelines followed to obtain those characteristics were determined. Telenko and Seepersad's 8-step method extracted environmentally conscious design guidelines using insights from

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dissecting products and performing life cycle analyses [20]. Additionally, guidelines were updated based on key features of redesign concepts generated during brainstorming exercises. **McComb et al [21]** 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 four steps in the design process.

When assessing extraction methods, the methods focused on analyzing final products appear limited by the lack of insight into the designer's true processes. While the protocol and case studies included intermediate and final solution sketches as well as verbal data, the heuristics are still based on hypothesized actions and not confirmed by the designer. This is not an attempt to discredit previous work, but instead to highlight the challenges faced when attempting to extract cognitive processes and explain how designers do design. In this study, interviews were used to identify a designer's set of heuristics. Of course, as with any self-reported data, the findings are limited to the perceptions and self-awareness of the participants. In previous studies, retrospective interviews following concept generation provided little impact on the heuristics discovered [10, 14]. 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. However, we hope that using interviews as the primary research tool will allow for uncovering heuristics collectively from the designers themselves. 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.

Eckert and Summers presented an overview of interviews as a research tool in engineering design [22]. 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 [23]. The interviews were the third leg of triangulation, where the other two methods included a visual product study and document analysis. Archiche et al. also used a 3-step process including interviews with follow-up questionnaires [24]. After an initial gathering of information, company managers were interviewed to discuss contexts, processes, inputs, and outputs relative to core front end (CFE) 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.

2.3 Heuristic Classification Methods

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 [12, 13, 15]. 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 [13]. 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 [16]. 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 [25]. Qureshi et al. separated guidelines by four general approaches to flexibility [18]. Moe and Jensen [26] 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. use a similar method to classify robotics design heuristics by breaking down the context into design phase, field of study, and action intent [27]. Subcategories for design phase and action intent were derived from Pahl & Beitz classifications [28]. 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 (DFE) guidelines using mind-mapping, a visual representation of brainstorming [29]. Reap and Bras categorized biological principles using a portion of grounded theory's constant comparative method (CCM) [30]. 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 [31]. 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 [30].

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 [32]. 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 [32]. 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 [33, 34]. CML allows engineers to better understand assumptions and potential flaws that form during concept formulation. Standards for concepts at each CML may be

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found in more detail in the CML Matrix [32, 33, 35]. 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 [33]. This usually includes high-level objectives, science questions, the science for addressing those questions, and a "cocktail napkin" sketch of the mission concept [35]. 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 [33]. The trade study explores impacts on science return, cost, and risk [35].

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 [36]. An entire A-Team study lasts about 6 weeks, beginning with client meetings [37]. Background information, goals, and requirements for the study are discussed at length during the client meeting [36]. 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 [37]. Studies take place in a designated area named 'left field', filled with reference material and whiteboards to promote creativity [38]. 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 [38]. Sometimes, the facilitator may be the study lead [36]. 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 [38]. 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 [32]. 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.

3. METHODOLOGY

The goal of this study was to extract heuristics used in the A-Team setting at JPL using interviews as the primary method for gathering data. The research plan received an IRB approval for human subject research. After approval, 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 ten 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 males and one white female interviewed. Three participants were between 21-30 years old, three between 31-40 years old, three between 51-60 years old, and one between 61-70 years old. Six participants were systems engineers, and the other four participants held management positions.

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

3.1 Part 1: Understanding Heuristics

In the first 10-15 minutes of the interview, participants spoke on their official and unofficial roles at JPL and within the A-Team. The researcher then gave an overview of the study and moved into a discussion focused on heuristics. Participants received a detailed definition of heuristics along with relevant examples of heuristics that engineers at JPL may potentially encounter. Prior to the interviews, the researchers gathered a broad range of example heuristics in spacecraft design from *Space Mission Analysis and Design* [39] to prevent fixation on a particular mission area or spacecraft subsystem. However, the number of examples presented varied based on the participant's understanding of heuristics. Some example heuristics used are shown in Table 1.

TABLE 1: 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

3.2 Part 2: Generating Heuristics

Once participants became more familiar with heuristics, they attempted to state as many heuristics as possible that they use in their own designs, particularly within the A-Team. Participants were given 30-35 minutes for heuristic articulation. The researcher asked follow-up questions as necessary to prompt the participant to express these heuristics in the desired "context - action" form. If the participant struggled to identify examples of heuristics in their own work, they were presented additional examples of heuristics for assistance. In many instances, the participant would state the heuristic as "context-action" without assistance from the researcher. Some example excerpts from the interview transcripts are presented next.

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

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

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

Participant H: "Often we'll have an exercise just to think about the figures of merit, then we ask the participants to keep them in mind as they are doing the multi-voting exercise. Instead of actually applying the figures of merit, we are priming them with what we hope they will make their selections on. That seems to be the less time constrained version of it, rather than saying if a concept is high, medium, or low on all these figures of merit. It could become very time consuming."
Researcher: "So, when you are multi-voting, keep in mind the figures of merit."
Participant H: "Yes, that's usually the more effective approach for time purposes."
Extracted Heuristic: **"**When multi-voting, consider how the concepts relate to each figure of merit."

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

Participant D: "...and we have about 16 people in the A-Team. Only 2 are full time, as I said, and we like studies to have between eight and 12 folks. When you get less than 8 you probably don't have diverse enough opinions to brainstorm and get the ideas all over the place, and if you get more than 18 people, 20 people it is really tough to control."
Extracted Heuristic: **"**When planning an A-Team study, design the study to have between 8-12 people."

3.3 Part 3: Characterizing Heuristics

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

As soon as a set of heuristics were documented from the interview, a survey was distributed via email to obtain more information about each heuristic. The survey was estimated to take ten minutes to complete. 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. Each participant's survey contained their own heuristics only. Characteristics obtained through survey questions include:

Source/Origin: Sources hypothesized by the researchers were placed in the survey, but the participant also had the choice of writing any source not listed.
Applicable Concept Maturity Levels: Participants selected the CML stage(s) where the heuristic is applicable. A "not sure" option was also provided.
Number of Years Used: Participants identify how many years they have been using the heuristic by selecting from various ranges provided.
Frequency of Use, Reliability, Evolution: Participants self-assessed how often they use a heuristic, how reliable that heuristic is to reach a satisfactory solution, and how often the heuristic evolves or tends to be updated. These attributes were graded on Likert scales ranging from 'never' to 'always', including a "not sure" option.

4. RESULTS AND DISCUSSION

From the 10 interviews, 101 heuristics were identified. Sixty-three heuristics were identified during phone interviews, and 38 were collected during in-person sessions. Similar heuristics from multiple participants were not combined, but the differences in presentation were kept untouched. 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.

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 2. 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 3 categories. In Table 2, 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 [40]. Action intent uses similarities in suggested actions from the data, and draws on our previous work using design phases from Pahl & Beitz [27, 28].

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 [32, 33]. In future work, all categories have potential to expand, and new categories have potential to emerge.

4.2 Survey Results

The survey results and analysis are presented in Figures 1-8 and give us more insight into potential characterization and evaluation of heuristics. Figure 1 shows that a clear majority of heuristics identified were 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. Not only are rules of thumb picked up through a designer's own experiences but the experiences of others as well. These are obtained by observing colleagues in a design situation or having them explicitly stated in a form of mentoring. Heuristics self-reported as picked up during A-Team studies may include planning heuristics specific to the A-Team or heuristics that participants have noticed other members use during a study. Outside of the A-Team, a designer having direct access

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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.

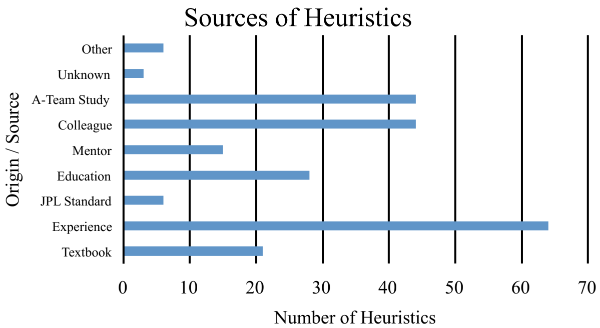

FIGURE 1: ORIGIN / SOURCE OF HEURISTICS

Figures 2-3 refer to the applicability of the heuristics in relation to concept maturity levels. The A-Team performs studies through CML 1-3, so it is understandable that the majority of heuristics are applicable at those levels. Most of these heuristics can be used across all three CML stages, or at least 2 of the 3. However, at some point the design becomes too mature for the heuristic to be used. In other words, the heuristic loses its value as the designer progresses through the design process. For A-Team members, the set of heuristics considered can be reduced by knowing the value a heuristic carries to a CML stage. Outside of the A-Team, this idea can be modified to fit design processes to assess value across design phases.

Figure 4 shows that the heuristics identified have most commonly been used for 2-5 years. This may reflect a number of factors including the youth of the A-Team, which has only existed since 2011. Any heuristics picked up from inside the A-Team studies would not likely be more than 5 years old. They may represent each participant's own design experience, and some may describe the timeline for heuristics becoming obsolete and replaced with new heuristics. Outside of the A-Team, this data could be used to represent reliability or evolution as a function of time or identify when it is time to update a heuristic. More information would be required to determine the effect any of these hypothesized factors have on the data. This is discussed further in the "Conclusions and Future Work" section.

Figures 5-7 show 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 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.

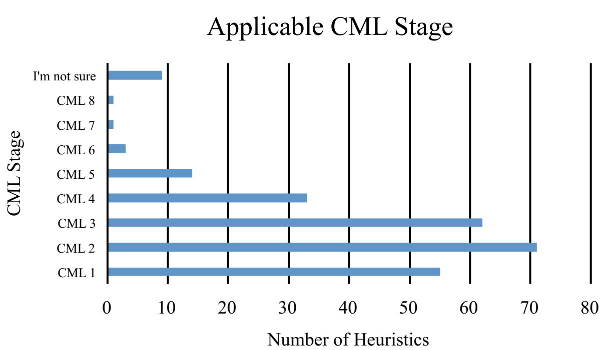

FIGURE 2: APPLICABLE CML STAGE FOR HEURISTICS

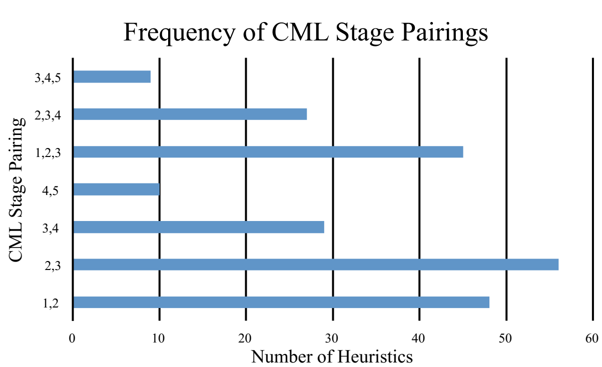

FIGURE 3: MOST COMMON CML PAIRINGS FOR A HEURISTIC

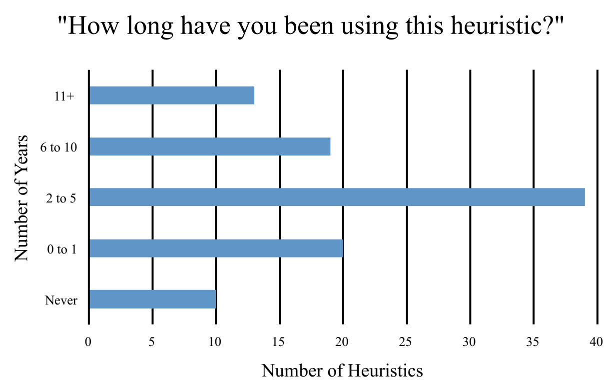

FIGURE 4: HOW LONG EACH HEURISTIC HAS BEEN IN USE

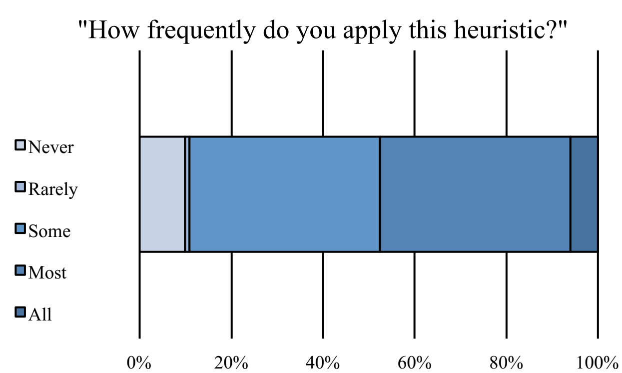

FIGURE 5: SELF-REPORTED FREQUENCY OF USE OF HEURISTICS

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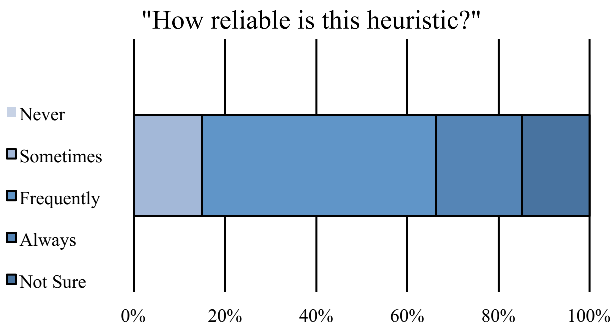

FIGURE 6: SELF-REPORTED RELIABILITY OF HEURISTICS

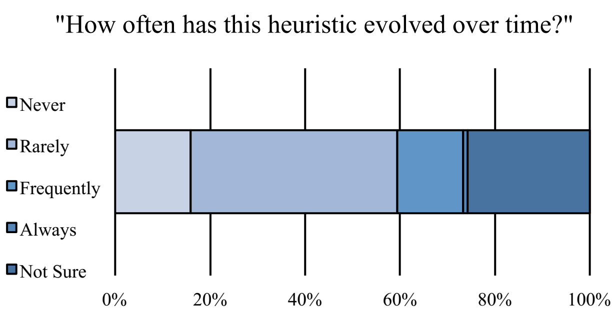

FIGURE 7: SELF-REPORTED EVOLUTION OF HEURISTICS

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 responses for evolution, reliability, and frequency were tested for correlations using Spearman's rank correlation coefficient, more commonly known as Spearman's rho. This was used instead of a parametric test because the data was ordinal, which makes a Pearson's correlation inappropriate [41]. Results from a Spearman's correlation test can provide information regarding the strength and direction of a monotonic relationship regarding two variables. All statistical analyses were done using the IBM SPSS statistics software package. Any survey question receiving a "not sure" was deleted from the analysis because it does not fall along the ordinal scale of the other responses.

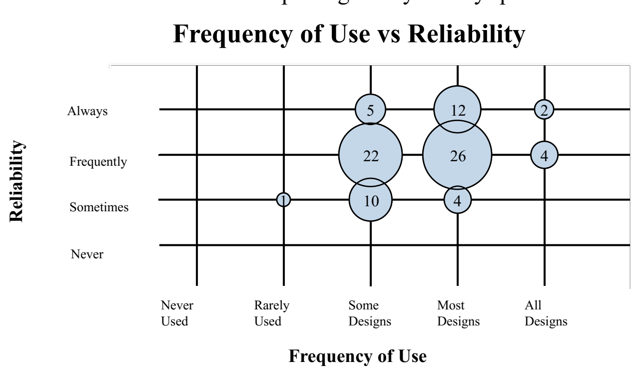

FIGURE 8: SELF-REPORTED COMBINATIONS FOR FREQUENCY AND RELIABILITY

The combination of responses for frequency of use and reliability of a heuristic are shown in Figure 8. A Spearman's correlation coefficient of 0.305 shows this relationship has a positive correlation. This means when the heuristic is used more frequently, the reliability tends to increase. This correlation has 2-tailed significance at the 0.01 level with a sample size of 86. This relationship makes sense because designers will use a rule of thumb more often if it continues to bring consistent results. On the other hand, a heuristic with inconsistent results is less likely to be retained by the designer. Examples of heuristics on each end of the scale are presented below.

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

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

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

Figure 9 shows combined responses for frequency of use and evolution of a heuristic. A Spearman's correlation coefficient of -0.385 shows this relationship has a negative correlation. This means a heuristic used more often also tends to evolve less often. This correlation has 2-tailed significance at the 0.01 level with a sample size of 75. It makes sense a heuristic is used more if it requires less analysis and updates. If the designer wants a "quick and dirty" method to move through the decision process, actions that do not require constant evaluation are more preferred. Repeated updates and analysis defeats one purpose of the heuristic itself, to save processing time. Examples of heuristics on each end of the scale are presented below.

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

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

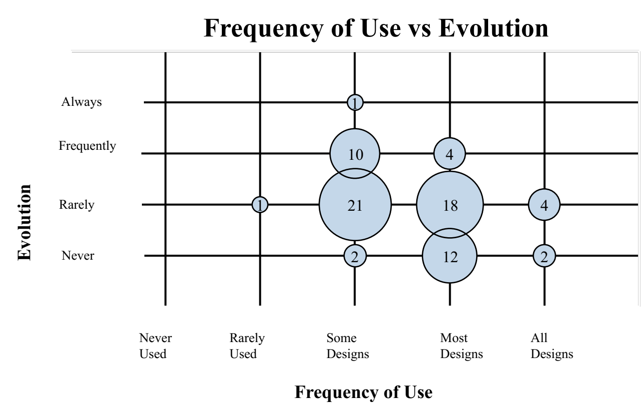

FIGURE 9: SELF-REPORTED COMBINATIONS FOR FREQUENCY AND EVOLUTION

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 10 shows combined responses for reliability and evolution of a heuristic. A Spearman's correlation coefficient of -0.435 shows this relationship has a negative correlation. This means a more reliable heuristic tends to evolve less often. This correlation has 2-tailed significance at the 0.01 level with a sample size of 72. A heuristic not properly updated is more likely to be misused, so heuristics requiring

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less updates will be more reliable over time. Overall, the correlations presented so far suggest that for reliable success, a heuristic should be broadly applicable for more frequent use and not changing over time for less evolution. Examples of heuristics on each end of the scale are presented below.

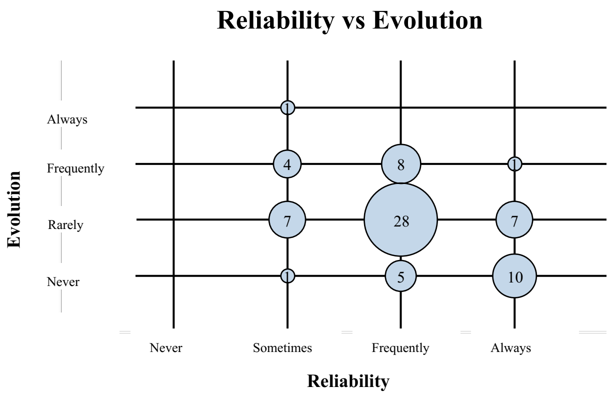

FIGURE 10: SELF-REPORTED COMBINATIONS FOR RELIABILITY AND EVOLUTION

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.

5. CONCLUSIONS AND FUTURE WORK

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. 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. This paper presents heuristics as reported by the participants and does not intend to recommend using the set of heuristics or guarantee successful application.

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. 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 artefact-focused heuristics limited to spacecraft design. In either case, it is important to maintain the true nature of the heuristic.

Improvement of the methodology may begin through better understanding of any "not sure" responses within the survey data. 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.

6. ACKNOWLEDGMENTS

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TABLE 2: HEURISTIC CLASSIFICATION SCHEME

Primary Area of Concern	Secondary Area of Concern	Action Intent	Example Heuristic
A-Team Study Design (27)	Pre-Study Planning (12)	Create Schedule / Timeline (11)	When presenting topics relevant to the study, keep the presentations short (about 10-15 minutes).
		Identify Resources Required (1)	When planning an A-team session, design the study to have between 8-12 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 multi vote 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 & Orbit Control (1)	If the mission location has a strong environmental force, use a balanced spacecraft to make the attitude control less massive.
		Structure & Mechanisms (2)	When designing a mission, consider putting multiple functions, such as an orbiter and a lander, onto one element.

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