Towards a Better Understanding of Solving Complex Problems Through Innovation Contests

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B.Eng. in Aerospace Engineering, May 2008, Carleton University

A Dissertation submitted to

The Faculty of
The School of Engineering and Applied Science
of The George Washington University
in partial satisfaction of the requirements
for the degree of Doctor of Philosophy

May 15, 2022

Dissertation directed by

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Acknowledgments

I want to express my heartfelt gratitude to those who have helped through this long process. Without your support, I could not have gotten through the valleys and reached the peaks.

To Dr. Zoe Szajnfarber: thank you for your input, patience, effort, and support throughout the years. I would not be on this path if not for you. You opened doors that led me to opportunities I would never have thought possible; I will be forever grateful for that. In guiding my work, your ability to cut through the noise and find the signal has helped me time and again. Thank you for taking a chance on me.

To my Dissertation Committee members: thank you for your sharp insights on this work. Your comments have helped make this dissertation a better product. I learned so much from our interactions and hope my insights have also opened your apertures to new areas.

To the members of Szajnlab, both past and present: you guys are the best. To Sam, Suparna, Zach, Isabel, Nik, Lydia, Jason C., Connor, Anthony, Amy, and Taylan, you have been dream colleagues. You have been supportive and empathetic when I needed friends, insightful and timely when I needed feedback. Thank you for extending a hand when I needed one. And thank you for listening to my rambles, early drafts, and more polished works. Every compliment and tomato has made this a better product and me a better person. You have a life-long friend in me.

To colleagues in the Engineering Management and Systems Engineering Department: thank you for your support. To Deniz, Amir, Lauren, Mike, and Azrah, thank you for your feedback on early versions of my work. It was much appreciated. I would also like to acknowledge the Department's help throughout my years as a student.

To colleagues at NASA: thank you for making this work possible. To Monsi Roman and Jenn Gustetic, thank you for opening the door to your respective programs. I appreciated the opportunity to learn from it and make it better. To Jason Kessler, Janet Sudnik, Dawn Turner, Dom Brewer, and Tony Kim, thank you for your support and assistance; you made me feel like a part of the team. To the interviewees at NASA and elsewhere, thank you for your participation and candidness.

To the ECAST Network: thank you for your partnership. Dave Tomblin, Mahmood Farooque, Ira Bennet, and the CSPO in DC team, you made a significant part of this work a possibility. I am grateful for this opportunity. Additionally, my thanks to the observers who helped me collect data during the citizen forum events: Charlie Balter, Rose Egelhoff, Gretchen Gano, Leigh Ann Mesiti, David Tomblin, and Richard Worthington.

To Karim Lakhani and colleagues at the Laboratory for Innovation Science at Harvard: thank you for being a welcoming host. You provided insightful comments and helpful feedback on my work. I very much appreciated and enjoyed being part of your lab.

Na mi majornan: un danki pa boso amor y sosten. Ya pa hopi aña, y te dia di awe, boso ta sigi inspirami: pa ser un mihor hende, pa persevera, pa tin pasenshi, y pa no perde mi metanan for di bista. Mescos cu boso ta orguyoso dimi, mi ta orguyoso di boso tambe.

Finally, to Carolyn: thank you for your patience, support, pep talks, editing, understanding, patience, and most importantly, your love.

Abstract

Towards a Better Understanding of Solving Complex Problems Through Innovation Contests

Problem-solving, which is core to an organization's success, is undergoing a significant shift. More and more, public and private organizations are shifting away from solely internal, expert-driven processes. Instead, they use crowdsourcing mechanisms, like innovation contests, to look for innovative outsiders. However, our understanding of how these work and how to use them largely rests on studies of consumer products or conceptual designs. The dynamics and outcomes of these simpler contests differ from those of complex systems. As such, we do not know how crowdsourcing's existing theoretical constructs, or the relationships between them, apply to engineering problems.

My dissertation addresses this gap by exploring crowdsourcing in engineered systems and extending current theory. Here, I draw on two multiyear fieldworks in NASA's crowdsourcing ecosystem: the Asteroid Grand Challenge and the Centennial Challenges Program. Using these rich data, I make four contributions across four essays, all expanding on existing theory on crowdsourcing. First, I create a benefits framework for complex innovation contests: organizations hosting a contest—the solution-*seeker*—benefit from access to technology and an expanded network, both from participants and industry advisors. Second, I show that a problem-*solver*'s technological trajectory is related to their success in an innovation contest: teams interested in pursuing opportunities in the organization's industry were more likely to win. Furthermore, this kind of solver—the *opportunist*—responded strongly to the seeker's in-kind prize incentives, which presents a new avenue for arbitrage. Third, I describe how problem formulation is a shared task between the solver and the seeker: the former can reformulate the latter's problem to introduce their expertise, resulting in useful solutions. Lastly, I describe how the seeker formulates a complex

problem for outsider input: I show how their actions to shape the solvers' solution space are guided by their knowledge of potential solutions and the problem-solvers' capabilities. Together, this work demonstrates a rich exchange between seeker and solvers, contrasting with the view of contests as a brief interaction. Here, seekers and solvers pay broad *and* sustained attention to the problem, exchange problem *and* solution knowledge, and drive technology *and* form partnerships over the long term.

These theoretical insights, and the practical levers they spell out, are both timely and needed. Without them, future endeavors are at risk of wasting the crowd's potential to help solve complex problems.

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List of Abbreviations

3DPH 3D Printed Habitat 11, 14, 21–29, 33–35, 52, 94, 95, 102, 103, 107, 108, 110, 111, 113, 114, 116, 183, 184, 186, 187, 189–194, 196–199, 202–206, 218, 220–222, 230, 232, 233, 240, 242, 244–246, 254, 260, 263–266, 273

ACME Additive Construction with Mobile Emplacement 184, 186, 187, 205, 206, 208, 245, 247, 254, 261

ADH Asteroid Data Hunter 16, 17

AGC Asteroid Grand Challenge 66

ARM Asteroid Redirect Mission 66, 67, 70–72, 78–81

BIM Building Information Modeling 232, 233, 240, 242, 267, 269, 270

CCP NASA Centennial Challenges Program 7, 21, 23–26, 29, 34, 42, 43, 86, 94, 96, 102, 161, 166, 168, 172, 176, 180, 182, 184–187, 190–192, 195–197, 199–201, 204, 206, 225, 231, 242, 245, 248, 260, 265, 267–269, 271

CHAPEA Crew Health and Performance Exploration Analog 265, 266, 269, 271

DOE U.S. Department of Energy 134

ECAST Expert and Citizen Assessment of Science and Technology 65

ECLSS Environmental Control and Life Support System 236

EMT Emergency Medical Technician 57

EPMC Executive Program Management Council 169, 170, 174, 182

HIT Human Intelligence Task 158, 159

ISS International Space Station 6, 7, 30, 209, 221, 226

JSC NASA Johnson Space Center 198, 265

KSC NASA Kennedy Space Center 21, 23, 30, 185–187, 208, 212, 219, 224–227, 239, 243, 263, 264

LaRC NASA Langley Research Center 202, 203

LOD Level of Development 233, 236, 270

METIS Materials Exposure and Technology Innovation in Space 263

MISSE Materials International Space Station Experiment 263

MMPACT Moon-to-Mars Planetary Autonomous Construction Technology 243, 263, 264, 271

MSFC NASA Marshall Space Flight Center 21, 23, 30, 185–187, 225, 243, 261, 263

MTurk Amazon Mechanical Turk 70, 71, 74, 77, 158

NASA National Aeronautics and Space Administration 6, 10, 11, 13, 14, 16, 17, 21, 23–31, 33–35, 38, 42, 46–49, 57, 65–73, 77–82, 86, 94–96, 102, 104, 107, 108, 110–114, 134, 161–167, 169–171, 173, 175, 176, 179, 181, 183–188, 190–193, 195, 196, 198–202, 204–210, 212–215, 218–220, 222, 224–226, 228, 231, 234, 239–241, 243, 244, 246, 247, 249, 250, 254, 257–261, 263, 265–271

OI Open Innovation 54, 57, 81, 83

PETG polyethylene terephthalate glycol 223, 261

PLA polylactic acid 261, 263

PSU Penn State University 225, 263

SME subject matter expert 24, 25, 27, 28, 163, 165, 167, 170, 172, 173, 176–182

SMEs subject matter experts 11, 17, 21, 23–28, 30, 32–35, 42, 44, 46, 47, 49, 86, 94–97, 102–115, 161–181, 183–193, 196–202, 204–264, 268

USACE U.S. Army Corps of Engineers 21, 185, 186, 205, 206

USAID United States Agency for International Development 185

VIF variance inflation factors 74

Chapter 1—Dissertation Overview

1.1 Introduction

My dissertation both calls for, and contributes to, more theory on crowdsourcing applied to complex problems, with a particular focus on innovation contests. Organizations have used this competitive problem-solving approach to gather new and useful solutions from outsiders. However, the current theoretical insights and their practical levers rest largely on contests that, for example, challenge consumer products or conceptual designs. These simpler contexts differ from the engineered system design problems often faced by technical organizations. Mirroring this difference, simple innovation contests differ in dynamics and outcomes compared to those where an engineered system is challenged. The literature lacks a theoretical grounding to apply innovation contests—and crowdsourcing generally—to complex problems; in contrast, the consumer product industry has been able to rely on strong theoretical work for the past decade or more. As such, we do not know if—or how—the relevant crowdsourcing constructs, or the relationships between them, apply. For organizations pursuing complex problems, the lack of theory could result in missed opportunities for gathering knowledge from the crowd, or wasted efforts to retool the crowd's solutions into ones that fit.

I intend this work to be the cornerstone for future studies: extending theory where needed and introducing a new view of innovation contests as framed by these problems. This introduction describes the relevant theoretical background for this dissertation. It summarizes the underpinnings of crowdsourcing and innovation contests and makes a case for extending theory to explain complex innovation contests. I then summarize my contributions to address this gap, each representing a separate chapter in this document.

1.2 Background and Positioning

1.2.1 Why Should Organizations Open Up?

For many organizations, solving problems is an important yet challenging activity (Nickerson and Zenger, 2004). This is particularly true for technical organizations: their profit-making or research pursuits mean they face complex, often new-to-the-world, problems (Nonaka, 1994; Hobday, 1998). These are in a class of their own for several reasons. First, the problem's many constituent parts do not interact straightforwardly (Simon, 1962; Holland, 1998; Maier and Rechtin, 2000) and often span multiple domains (Weck et al., 2011; Szajnfarber and Vrolijk, 2018). Second, addressing them requires both broad *and* deep knowledge, which can be costly to gather if the organization does not already possess it (von Hippel, 1994; Tushman, 1977; Cohen and Levinthal, 1990). Worse still, it can exceed the problem-solving capacities of the single solver—be they an individual or an organization (Simon, 1956; Cyert and March, 1963). Third, and relatedly, their knowledge-gathering and problem-solving effort itself must be coordinated among various contributors (Baldwin and Clark, 2000; Ulrich, 1995; Brusoni et al., 2001), which can significantly impact their success (Henderson and Clark, 1990; Colfer and Baldwin, 2016). Practically, projects that address complex problems have large budgets and even higher stakes—failing to solve the problem promptly might mean billions of dollars of cost overruns (Collopy and Hollingsworth, 2011), a loss of prestige (Vrolijk and Szajnfarber, 2015), and a high risk to life and property (Columbia Accident Investigation Board, 2003; Leveson and Turner, 1993). Efficiency at searching for knowledge to create a solution is, thus, critical.

Both scholars and practitioners have advocated for the input of outsiders in searching for this knowledge. Innovation scholars arrived at this conclusion drawing on

Simon's seminal work on the limits of one's cognitive abilities (1957; 1972). While this has influenced a great many fields, what is most relevant for my work is its implications on the study of expertise (e.g., Chase and Simon, 1973; Bedard and Chi, 1992; Collins and Evans, 2002). In particular, studies of experts and their behavior have shown that these individuals are limited[1] in their information-processing capacities. The structure of their domain knowledge becomes stuck (Dane, 2010), meaning they: are less able to view their problems from different perspectives (Hinds, 1999); have difficulty adapting to changes in known problems (Cañas et al., 2003); and, rely heavily on known approaches or solutions, sometimes in favor of better ones (Bilalić et al., 2008; Lovett and Anderson, 1996). Scholars have reported these, and their impact on the organization, in various settings (Almandoz and Tilcsik, 2016; Acar and van den Ende, 2016; Bayus, 2012). These studies all describe a similar approach to address these limitations: if insiders are stuck in the views of their domain, then organizations should open up to outsiders who are stuck elsewhere (von Hippel, 1994; Dane, 2010).

On the practitioner side, Bill Joy—of Sun Microsystems fame—said it best. In the 1990s, he once proposed that "no matter who you are, most of the smartest people work for someone else" (Manville, 2015). This was a remarkably candid statement at the height of his company's market position in computer workstations. With it, he acknowledged that solutions to the complex problems that they were facing did not only come from those internal to their organization, even occupying this top spot.

1.2.2 How Should Organizations Open Up?

Chesbrough used the term *open innovation* to describe and characterize purposeful knowledge flows into (and out of) the organization (2003). While innovation scholars had been studying how organizations cross organizational and domain boundaries since the 1970s (e.g., Tushman, 1977; Allen, 1977), this research paradigm formalized

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[1] Scholars have studied the limitations of expertise under constructs like *cognitive entrenchment*, *Einstellung*, and *(design) fixation*. I have coarsely summarized across these, highlighting the specific ones that crowdsourcing addresses.

the study of “outside-in innovation” (Enkel et al., 2009; West and Bogers, 2014). Addressing the experts’ shortcomings, this paradigm rests (partly) on the proposition that “valuable ideas can come from inside or outside” the organization (Chesbrough, 2006, p. 1)—opening up internal innovation processes to external contributors. But, importantly, it also laid the groundwork for asking *who* we should be opening up to.

One answer to that question is *anyone* (Howe, 2006). The solution-seeker, stuck in their view of the problem or domain, might not be able to identify who has the relevant knowledge or its best expression. In this framing, it would be too costly to either search for the knowledge internally or create the inflow by searching for the right problem-solver. Instead, scholars argue that the search for this knowledge should be outsourced to “anyone who deems themselves qualified to solve the problem” (Jeppesen and Lakhani, 2010, p. 1016)—and thus, *crowdsourcing* (Afuah and Tucci, 2012). Those who self-select to try to solve the problem—who are likely not known to the organization—would be searching for the relevant knowledge locally (Cyert and March, 1963; Laursen, 2012). That is, drawing on their own background and/or what is (easily) available to them (Lüthje et al., 2005; von Hippel, 1994; Baer et al., 2013), so “they do not have to go outside their immediate knowledge neighborhood.” (Afuah and Tucci, 2012, p. 360).

Crowdsourcing shifts the burden of finding the right external solver to the solvers themselves. An outsider decides to tackle the problem because they recognize it and (think they) have the relevant knowledge to solve it. The hard part of this search for knowledge—the *locus of innovation*—shifts to whoever decides to tackle the problem (Lifshitz-Assaf, 2018). What remains is for the seeker to pick, and formulate, the right problem—no easy task either (Szajnfarber and Vrolijk, 2018; Wallin et al., 2018; Ehls et al., 2020). Nevertheless, shifting this burden opens up opportunities for good solutions from unexpected corners. The canonical example of this is the Longitude at Sea Challenge in 1714: an innovation contest to determine the longitudinal position of a ship (Spencer, 2012). Even with Sir Isaac Newton predicting that an astronomer would win, ultimately, the solution came from a clockmaker (Sobel, 2005).

But how to motivate outsiders—with (potentially) useful knowledge—to contribute to a problem they might not know or care about? Here, crowdsourcing draws from the tournament theory literature. Seekers place a bounty on the problem, creating an external—and artificial—need. This places a value on the solution that outsiders can relate to. Solvers compete for this "artificial" value of the solution, inducing dynamics seen across contests (Taylor, 1995; Davis and Davis, 2004; Morgan and Wang, 2010). Solvers participate to satisfy their (intrinsic or extrinsic) motivations (Mack and Landau, 2015; Acar, 2019). And the quality of their solving efforts impacts their chance at a prize (Terwiesch and Xu, 2008). In the end, the seeker and (the winning) solver exchange the prize for the solution. With that transaction complete, the solvers—both winners and losers—return to their baseline.

1.2.3 Innovation Contests as a Focus

The innovation contest is, thus, a competitive form of crowdsourcing under the wider umbrella of the open innovation paradigm. Both the popular press and the academic literature have described successes of innovation contests in solving problems: they have helped Goldcorp Inc. find gold (Blohm et al., 2013; Tischler, 2002); they have helped develop software products for Dell (di Gangi and Wasko, 2009; Bayus, 2012); and they have even helped tackle COVID-19 (Vermicelli et al., 2021; The Montreal General Hospital Foundation, 2020).

These successes seem to suggest that innovation contests—and crowdsourcing generally—can, and should, be used to solve any problem. In fact, these activities are occurring more frequently, growing in complexity and scale. Both firms (Jeppesen and Frederiksen, 2006; Ogawa and Piller, 2006) and government agencies (Gustetic et al., 2015; Ogawa et al., 2011; Schmidthuber et al., 2019) are experimenting with the crowd's input. However, there have also been failures using this approach. A notable example is BP's contest to clean up the Deepwater Horizon oil spill. Despite the 120,000 solutions to seal the well or clean up the affected waterways, the solvers' efforts "yielded very little in terms of results" (Goldenberg, 2011) and did not translate into a solution that made it to implementation (Alexy et al., 2012). This failure, and others like it, may be examples of applying this approach incorrectly (Dahlander and Piezunka, 2020)—something that should give us pause.

1.3 Implications of Simple versus Complex Problems on Innovation Contests

Below, I expand on the warning highlighted by several crowdsourcing failures: the kind of problem—specifically, simple versus complex ones—might change the dynamics of the contest.

Organizations have used "innovation contests[2]" to tackle a range of problems. But the literature uses that term to describe the *approach* to solving the problem, not *what problem* is being solved. Consider Threadless' contest(s): this fashion company taps into the crowd for new designs regarding their main seller, graphic tees (Ogawa and Piller, 2006). Here, solvers submit print designs for a chance at a prize. Contrast that with National Aeronautics and Space Administration (NASA)'s Astronaut Glove Challenge: through this contest, the agency tapped into the crowd for new designs regarding the dexterity of spacesuit gloves on the International Space Station (ISS) (Gustetic et al., 2015). Here, solvers designed, developed, and tested their glove prototypes under vacuum pressures for a chance at the prize. In both examples, the seeker put a bounty on an important problem, and looked to outsiders for their knowledge and solutions. But by any metric, their focal problems are clearly of different complexity.

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[2] Also termed inducement prize, innovation tournament, innovation prize, prize challenge, or prize contest.

Under the crowdsourcing umbrella, scholars have studied contests that fall closer to t-shirt design than an ISS spacesuit prototype. These have included contests for conceptual design ideas (e.g., Ruiz et al., 2020; Magnusson et al., 2014; Pollok et al., 2019a), which could be tackled by a single person instead of requiring a team of people; contests that challenged the design and development of consumer products, like Threadless.com hosts (e.g., Poetz and Schreier, 2012; Füller et al., 2011; Wooten and Ulrich, 2017), where the required knowledge is widely available among the general population instead of requiring unique combinations of specialized skills; or contests that required only a single discipline instead of several (e.g., Paik et al., 2020; Lakhani et al., 2013a, 2010). Thus, the understanding and implementation of innovation contests rest primarily on insights whose context differ greatly from complex problems.

This could be a problem for complex innovation contests. Why? How the differences between complex and simple problems manifests in their respective innovation contests might limit how (well) these insights apply. For example, one major difference between simple and complex contests is who participates. Solvers in complex innovation contests are usually teams; those in simple contests are usually individuals (cf. Szajnfarber et al., 2020; Jeppesen and Lakhani, 2010; Kay, 2012; Murray et al., 2012). Innovation platforms that house these contests have noticed this difference as well. Platforms that focus on complex problems—like the NASA Centennial Challenges Program (CCP)—describe teams of participants. Conversely, platforms like Threadless and InnoCentive shine a light on individual solvers. This difference implies a different unit of analysis across the two kinds of problems: an individual versus a team. With it comes a shift away from individual limits to local search and a step-change improvement in their cognitive abilities[3].

Another difference between simple and complex contests is solvers' motivations—both their relative importance and how they manifest. Studies have shown that

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[3] See, e.g., Almandoz and Tilcsik (2016) for an example of how a team can work together to overcome the cognitive limitations of their individual members.

intrinsic motivations—like having fun—are *the* reason to participate in simple contests (Mack and Landau, 2015), and even predict the (high) quality of their submissions (Frey et al., 2011; Acar, 2019). In contrast, having fun ranked much lower in importance of the motivators among surveyed participants in a complex contest (Murray et al., 2012). Differences between simple and complex contests persist even in cases when extrinsic motivations—like winning a prize—dominate both contexts. For example, extrinsic motivations dominated both a contest looking for ideas to improve student services and one to demonstrate lunar-lander prototypes. However, the desire for a monetary prize dominated the former (Ihl et al., 2019), whereas only one team out of seven mentioned the contest's monetary prize in the latter (Kay, 2011). Not understanding these differences could lead seekers to set prize incentives that do not match what is optimal or expected by potential solvers.

These differences have shaped the view of innovation contests to be brief interactions that are transactional in nature (see also Randhawa et al., 2019). This view is a holdover from the innovation contest's origins in tournament theory (Frick, 2003), where the focus was on the exchange of solution knowledge for (a chance at) the contest's prize (see, e.g., Taylor, 1995). Through this lens, the seeker only sees the contest as an ad-hoc interaction (cf. Paik et al., 2020; Pollok et al., 2019b; Beretta, 2019), where they engage with solvers temporarily (Howe, 2006)—reminiscent to gig-workers (Szajnfarber et al., 2020; Shergadwala et al., 2020). Likewise, short-term payoff is a strong component of solver motivations, for example having fun (MacCormack et al., 2013; Morgan and Wang, 2010) or getting paid (Terwiesch and Xu, 2008; Ihl et al., 2019). Even when the interaction can be (approximately) continuous, the emphasis is on the transaction. The seeker will often view solvers only as solution-providers on innovation contest platforms (cf. Sieg et al., 2010; Pollok et al., 2019a). Sometimes, the platform reinforces this view too (Natalicchio et al., 2017): they provide seekers with a problem-solving service (Morgan and Wang, 2010), with an eye on how many problems they will challenge (Lakhani et al., 2010).

I summarize the transactional view of innovation contests in Figure 1.1. In it, the solver (solid line) interacts with the contest and the seeker (dotted line) momentarily. In this brief interaction, the solver transfers their solution knowledge to the seeker. In turn, the seeker transfers the contest's prize to the (winning) solver. Both return to their baseline post-contest.

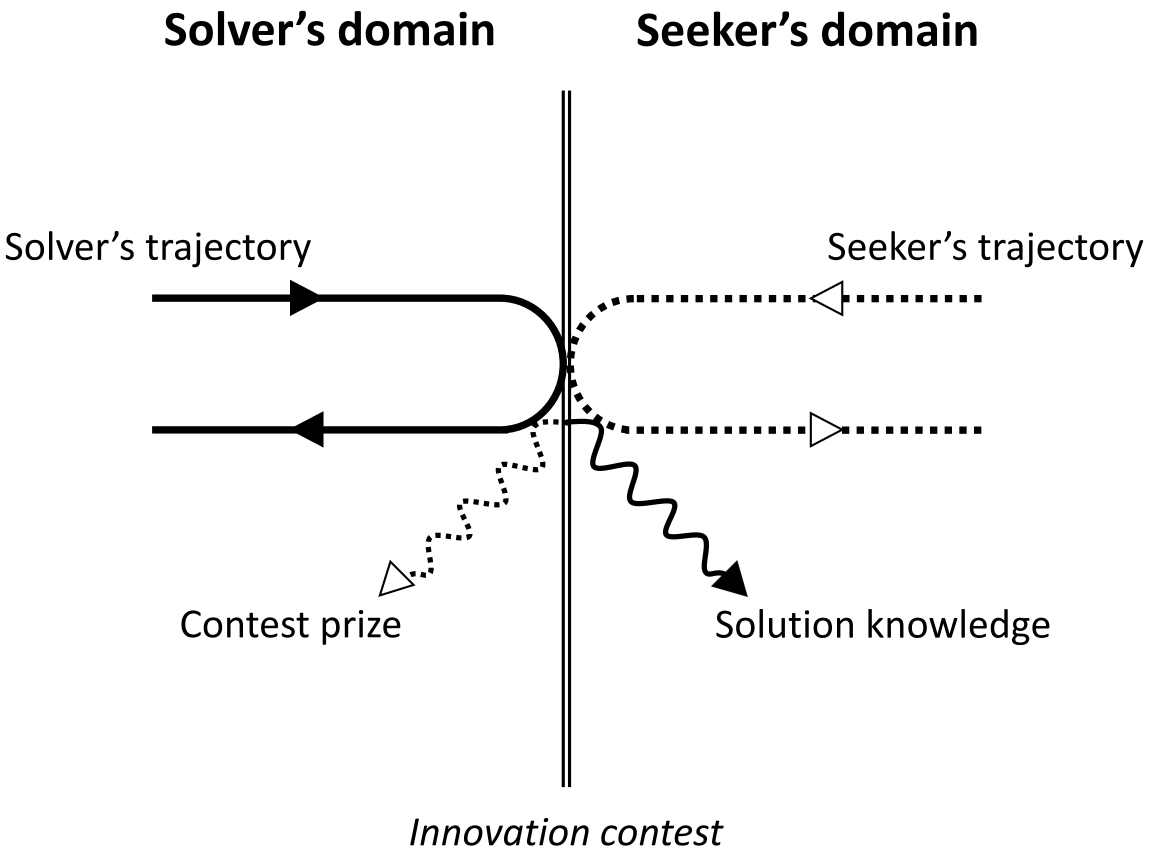

Figure 1.1: The transactional view of innovation contests, which centers around a brief exchange of solution knowledge for a prize

In sum, differences between simple and complex problems shape the differences between innovation contests. In addition to those summarized above, other relationships between constructs may also differ when the kind of problem changes. Since existing theory on innovation contests is (mostly) built on simple problems, new theory needs to be created to take these dynamics into account. So far, only a small handful of scholars have recognized this gap.

For example, Murray et al. specify that their insights do not apply to "well-defined (albeit difficult) problems that often require only limited time commitment [...] or involve matching or adapting existing solutions to problems" (2012, p. 1779) (see also Piller and Walcher, 2006). Per Afuah and Tucci (2012), contests that challenge simple problems are more likely to see crowdsourcing successes. Szajnfarber and Vrolijk (2018) go a step further and describe how the complexity of the problem changes the contest's outcomes: increased complexity may reduce the number of capable solvers because of the cross-domain skill requirements to solve it. These works notwithstanding, the crowdsourcing literature does not distinguish how differences in simple versus complex problems impact how theoretical insights apply across different contests.

1.4 Research Gap

Known differences between simple and complex problems—e.g., their varying cognitive and domain requirements—imply that their innovation contests might differ as well. The risk is that existing theory, built studying simple contests, might apply poorly to contests challenging engineered systems. We might not observe the same outcomes when applying the same insights. The differences in the preceding section describe the need for new theory on complex innovation contests that describe its dynamics and provide new levers for future practitioners.

Extending crowdsourcing theory into complex problems is timely. More and more, technical organizations are looking to employ this tool to (help) solve their complex problems. For example, Airbus challenged teams to create quantum algorithms to optimize cargo loading (Benquet, 2020). GE incentivized ideas to increase the (low-carbon) electricity supply in Taiwan (Zulkiply, 2021). NASA has two challenges where participants will develop and demonstrate technologies needed for long-duration missions on the moon (Porter, 2020a,b). And a cooperation between Vale, BHP, and

Rio Tinto searched for power delivery solutions for their zero-emission large-haul trucks (Rio Tinto, 2021). These, and other, organizations have placed complex innovation contests firmly in their path. Without the kinds of insights I call for, future endeavors are at risk of under-leveraging the crowd at best, or wasting efforts at worst.

1.5 Overview of Contributions

Below, I summarize the contributions of this dissertation and how they extend theory on complex innovation contests. These are presented across four essays, each addressing (a) specific research question(s). In addition to their theoretical implications, the essays also describe the implications for practitioners looking to craft their next contest. Lastly, this work also includes materials supporting the analyses that produced the contributions.

Chapter 2: "Who Provides What and When" As I laid out above, an innovation contest is an effective way to address an organization's technical needs. Relying on its pay-for-success and winner(s)-take-all format, organizations have received high-quality solutions from these contests. These have provided them with the novel knowledge to address their need at lower costs than solving them internally. These successes drove scholars to focus on strategies that enhance the resulting solutions. However, the solution, and the knowledge required to create it, is but one part of successfully addressing a complex problem. As such, a narrow focus on solutions might ignore other benefits that are also important to these organizations.

My work leverages an in-depth case study of NASA's highly successful 3D Printed Habitat (3DPH) Challenge; I analyzed how it benefited the relevant NASA subject matter experts (SMEs). The resulting framework characterizes the range and sources of potential benefits across different stages of an innovation contest, some of which were more valuable than the solutions. These findings emphasize the need to broaden the existing focus on solutions and highlight new opportunities for practitioners to address their needs through innovation contests.

Chapter 3: "The Opportunists in Innovation Contests" The use of the term "the crowd" to describe those who participate in innovation contests can mask their richness. They vary in background, affiliation, expertise, and even number of people contributing to a single entry. These differences are important: studies of innovation contests have shown that certain kinds of solvers are more likely to successfully solve the problem and win. However, these studies diverge on *who* they are and offer no guidance on *what* attracts those kinds of solvers. Additionally, the differences in cognitive and knowledge requirements between simple and complex problems may also influence who participates in the respective innovation contests and why.

To address this gap, I examine various solvers across several different complex contests. Among the competing theories on good solvers, I establish that the solvers' intended trajectory was the most important distinguishing characteristic for finalists in my data set. These *opportunists* viewed the contest as the start of a new pursuit instead of a temporary undertaking. Additionally, they were the only ones reliably motivated by the seeker's in-kind incentives to participate when their trajectory aligned with the seeker's domain. These results show a distinction in the mindset of (some) solvers in complex versus simple contests: the contest is a springboard to new opportunities. Thus, the (seeker's) in-kind incentives carry more weight for these solvers because they align with, and support, the solver's planned trajectory better than a monetary prize alone. These insights provide an understanding of the dynamics of solvers in complex contests and a concrete lever for influencing who shows up to solve.

Chapter 4: "Let's Meet Somewhere in the Middle" Crowdsourcing excels at leveraging the distant expertise of outsiders. Yet, many successes have relied on serendipity: the right solver recognizing that they have relevant non-domain knowledge and correctly applying it to solve the seeker's problem. I contend that leveraging distant solvers' knowledge systematically requires rethinking the problem formulation process. Specifically, both the seeker and the solver have a role in determining the problem and how it is solved. This is especially true when complex problems are challenged: the relevant knowledge is not ubiquitous, and the problems' formulation can misdirect the solvers' search for it. To this end, I introduce the *formulation bridge*, which conceptualizes formulation as a shared effort.

I explored this concept through an empirical study. NASA engaged a group of non-space individuals on a spacecraft design problem. I observed how NASA communicated the problem, how the individuals solved the problem, and how NASA evaluated solutions. In my data, two-thirds of the useful solutions stemmed from reformulated problems. These solutions were more likely to be deemed useful when they leveraged knowledge that was local to the solver. Additionally, information transfer between solvers and the seeker also played an important role: reformulated problems were positively related to useful solutions when individuals provided more information on their solutions, transferring more information to the organization. My findings have important implications, both for theory on problem formulation and organizations' practice of structuring engagements with distant outsiders.

Chapter 5: "To Impose, To Incentivize, or To Subsume" Technical organizations regularly face complex problems crucial to their success. While the literature has proposed various approaches to tackle them, one approach advanced by innovation scholars is crowdsourcing: gathering input from individuals outside of the problem's focal domain or industry can mitigate some of the limits of their experts. To do so, the seeker must translate their need into a problem statement, formulating their problem for outsider input. This is a difficult task, however. On the one hand, the seeker must bound and delegate what they want to be explored. On the other, they must navigate the (at times unknown) limits of the solvers' capabilities. While our understanding of crowdsourcing grows, scholars note our lack of understanding of this step in that process: we do not know how the seeker formulates problems and cannot adequately guide them on how they should.

To address this gap, I examine the formulation process of several complex contests. Using detailed case narratives, I inductively captured the seeker's three problem formulation actions and why they chose them. The seeker chose to *impose*, *incentivize*, or *subsume* different parameters as they crafted the problem statement—each action producing less restrictive rules from the solvers' perspective. I also found that the choice between these actions depended on the seeker's knowledge of potentially good solutions and solvers' limits. The more they knew about solutions, the more restrictive actions they took. However, *only* when the seeker possessed high knowledge of the solutions did they accommodate solvers' limitations. Two of these actions, impose and incentivize, mirrored normative approaches to design complex engineered systems in the systems engineering literature: requirement allocation and objective allocation. The third, subsume, was the seeker's way of mitigating undesired solution variety when other actions were out of the solvers' reach. More broadly, subsume represented a new way to address solving uncertainty across organizational boundaries. These findings unpack the problem formulation process, connect the crowdsourcing and systems engineering literatures, and provide practitioners with a better-defined suite of tools to formulate their contest problem.

Supporting Materials The appendices support the analyses in the above essays. Appendix A describes coding processes for the analysis in Chapter 4. Appendices B and C are vetted case narratives of NASA's CO_2-to-Glucose Challenge and 3DPH Challenge, respectively. They detail a chronological account of the formulation of the crowdsourced problems within these contests. These, along with the coding data in

Appendix D, formed the basis for the work in Chapter 5.

1.6 Summary

The differences between simple and complex innovation contests highlight a need to extend existing theory on crowdsourcing. The four essays in this dissertation contribute to this gap, both individually and collectively. Individually, they: create a framework of the benefits of complex innovation contests; show that a solver's technological trajectory is related to contest success; explore how problem formulation is a shared task between the solver and the seeker; and, describe how the seeker formulates a complex problem for outsider input. Collectively, they demonstrate that the existing view of innovation contests as brief interactions between seeker and solver(s) is lacking, especially when applied to complex problems. Instead, seeker and solvers share a rich exchange during their prolonged interaction: drawing broad *and* sustained attention to the problem, exchanging problem *and* solution knowledge, and driving technology *and* forming partnerships over the long term.

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Vrolijk, A., Roman, M. C., and Szajnfarber, Z. (2022). Mapping the Benefits from Innovation Contests. *Research-Technology Management*, 65(1):29–38.

Chapter 2—Who Provides What and When

Mapping the Benefits Stemming from Innovation Contests[1]

2.1 Introduction

Organizations, both public and private, are increasingly turning to innovation contests to help solve their complex problems (Chesbrough and Bogers, 2014; Randhawa et al., 2019). Since the days of the Longitude Prize of 1714 (Spencer, 2012), these contests have successfully been used to gather (at times) novel solutions by competitively outsourcing their development (Jeppesen and Lakhani, 2010; Afuah and Tucci, 2012; Terwiesch and Xu, 2008). More recently, organizations like the NASA and Siemens have embedded this tool in their innovation processes—regularly challenging complex problems, even in times of crisis (Lifshitz-Assaf, 2018; Lakhani et al., 2013b; Vermicelli et al., 2021).

At the same time, their increased usage has invited more scrutiny. Specifically, the value of innovation contests has been called into question when its solutions do not benefit the organization. For example, after the Deepwater Horizon disaster, BP's call for ideas gathered 43,000 submissions from the crowd. Yet, this effort was deemed a failure: it "yielded relatively little in the way of results" for BP (Goldenberg, 2011, para. 5), and no solution made it "all the way" to implementation (Alexy et al., 2012, p. 117). Similarly, while the crowd's solutions successfully solved NASA's Asteroid Data Hunter (ADH) Challenge (Paik et al., 2020), the agency never used any of the crowd's solutions to detect asteroids (Gustetic et al., 2018). Considering

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[1] This is an Accepted Manuscript of an article published by Taylor & Francis in Research-Technology Management on January 6, 2022, available online at: `http://www.tandfonline.com/10.1080/08956308.2022.1993683`.

the literature's focus on (the knowledge contained in) the contest's solutions (Afuah and Tucci, 2012), lackluster performance or a failure to adopt raises concerns about their use (McCausland, 2020). Here, scholars have taken note of these kinds of failures and have called for approaches to mitigate them (Chesbrough and Brunswicker, 2014; Piezunka and Dahlander, 2015).

However, we contend that this focus is too narrow: solutions are but one benefit of innovation contests. NASA's work to defend the Earth from large asteroid strikes stretched back to the mid 1990s. But its partnership with Planetary Resources Inc. to support the ADH Challenge marked the first collaboration with private industry to address this threat. Their partnership also showed the planetary defense SMEs how they could collaborate with other non-traditional partners, like Verizon Wireless and Nvidia Corporation. Notably, these benefits were independent of the solutions received from the ADH solvers. In this vein, our paper cautions against a narrow focus on the solutions: the innovation contest's value does not—solely—equal the performance or adoption of the winning solution. Instead, we clarify the broad range of benefits that this tool can provide. Without this insight, practitioners might be ill-prepared to take advantage of a contest's other benefits when those opportunities present themselves.

Specifically, our work took an empirical approach to clarify *who* provides *what* benefits and *when*. Over the course of five years, we gathered qualitative data on how an organization benefited from challenging one of their key problems. From these data, we constructed a framework that describes how these benefits are distributed and who provides them across the different stages of an innovation contest. Our findings emphasized the importance of the non-solution benefits of innovation contests. In our setting, they were more valuable than the solutions, appeared throughout the contest process, and did not only stem from the solvers. Based on our results, we discussed how scholars should consider a broader perspective on the benefits of these contests.

We also provide guidance for practitioners to gear their future innovation contests accordingly.

2.2 Background

Innovation contests are a competition between problem-*solvers* for a prize set by a solution-*seeker* (Chesbrough and Bogers, 2014; Howe, 2006; Jeppesen and Lakhani, 2010). Broadly, each contest has four stages (Paik et al., 2020; Kiran and Sharma, 2021; Szajnfarber and Vrolijk, 2018; Ruiz et al., 2020; Zobel, 2017): formulate, solve, review, and absorb. First, the seeker picks a relevant topic that they deem suitable for a contest and describes the problem that will be challenged. Second, the seeker broadcasts the problem and promotes it widely. People in the crowd self-select to participate, and begin creating their solution(s). Third, the seeker receives the solvers' submissions, reviews them, and selects a winner based on prespecified performance metrics. Lastly, the seeker decides whether and how to absorb the (set of) solutions—and their knowledge—into their organization. We summarize these stages in Figure 2.1.

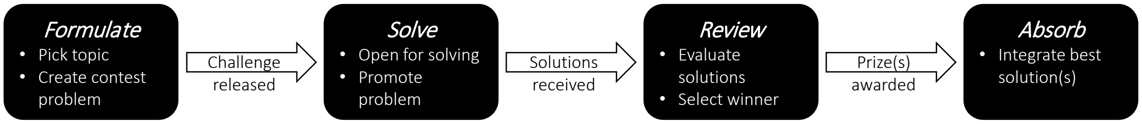

Figure 2.1: Summary of the innovation contest process

These contests are "designed to produce important innovations" (Morgan and Wang, 2010). They address the seeker's need by solving their problem, and have often delivered solutions that are both novel and high-performing (Hitt, 2007; Johnston, 2012; Howe, 2006; Spencer, 2012). With this in mind, the literature has focused on gathering solutions and their associated knowledge more efficiently (see e.g., Afuah and Tucci, 2012; Piezunka and Dahlander, 2015), or measure when—and how—outsiders can outperform the (seeker's) insiders (see e.g., Jeppesen and Lakhani, 2010; Poetz and Schreier, 2012). By and large, the focus has been on the solutions and exploring different ways to improve a contest's yield. Potential benefits to the seeker—like connecting to diverse participants and stimulating outsiders to investment in the focal domain—have been framed in this light as well.

With a focus on solutions, connecting to diverse participants is considered a benefit *because* these individuals increase the chances of novel solutions (Jeppesen and Lakhani, 2010; Franke et al., 2013). Innovation contests might attract experts, and reveal kinds of expertise, that the seeker might not have known about before (Szajnfarber et al., 2020; Piller and Walcher, 2006). Their diversity is their strength. Differences in domain expertise between the seeker and the solvers can lead to design choices that are familiar to solvers but not to the seeker (Afuah and Tucci, 2012). The result is a diverse set of (novel) solutions—some outperforming internal ones (Poetz and Schreier, 2012)—and a broader understanding of the design space (Franke et al., 2013; Kay, 2011).

Similarly, investment from outsiders is considered a benefit *because* it lowers the seeker's costs of solving their problem. Even in their earliest descriptions, innovation contests were considered a "means to obtain a given quality of [innovation] at as low a cost possible under various market conditions" (Fullerton et al., 1999, p. 635). Innovation contests outsource these costs by shifting who solves the problem (Afuah and Tucci, 2012; Lakhani et al., 2013c); and then only rewarding their success, not compensating their effort (Terwiesch and Xu, 2008; Taylor, 1995; Fullerton et al., 2002). For example, the empirical study performed by Paik et al. (2020) showed a lower cost of the knowledge obtained through a contest compared to an equivalent internal (or contracted) exploration. Furthermore, the seeker's burden is also reduced (if and) when the solvers commercialize their solution (Murray et al., 2012; Kay, 2011), where they mature the technology to provide it as a service or product for the seeker (Gustetic et al., 2015).

However, this focus on solutions risks ignoring other important benefits. Through this lens, one might classify a benefit by asking “how does it benefit the solutions?” If a strong connection cannot be made, it is either considered a byproduct, or ignored.

Currently, only a few studies have asked the broader question,“how does it benefit the seeker,” thereby taking a broader view of benefits (see e.g., Terwiesch and Xu, 2008; Murray et al., 2012; Schmidthuber et al., 2019; Chesbrough and Di Minin, 2014). In particular, Murray et al. captured how “education, attention and community building [were] as important as the technical solutions themselves” in the Progressive Automotive XPRIZE (2012, p. 1780). Along these lines, practitioners themselves have also noted that the benefits of innovation contests as inherently important, not just important to the solutions. For example, broadcasting the problem raises the visibility of the seeker and their need. Here, the contest can serve as a “north star” (Gustetic et al., 2018, p. 2), drawing the attention of the public as well as those in their own domain. It also pushes their message to audiences that traditionally do not interact with the seeker’s organization and domain, (Gustetic et al., 2015).

These, and other, papers form a growing collection that consider a broader view of the benefits of innovation contests. However, it lacks a study that systematically examines the full range of benefits, who they stem from, and when they arise in the process. Our study fills this gap.

2.3 Case Study

Our study explored how a seeker benefits from their innovation contest across its different stages. Prior studies have described the benefits of the contest’s solutions at length. However, less attention has been paid to other benefits despite how important they are to practitioners (see e.g., Murray et al., 2012; Gustetic et al., 2018, 2015). To better understand them and create grounded and actionable insights, we used inductive research methods as recommended by the literature (Edmondson and Mcmanus, 2007; Eisenhardt et al., 2016)—leaning on qualitative data and analysis techniques to gather and analyze rich, real-world data (Miles and Huberman, 1994).

Our setting for this study was NASA's 3DPH Challenge, one of several contests in the CCP portfolio. Missions to the Moon or Mars are incredibly expensive, and reducing their costs can enable NASA to do more science and exploration. For the upcoming crewed missions to those planets, NASA SMEs have proposed using resources that are locally available, as bringing them from Earth would "not be practical" due to the costs of launch. Planetary additive construction follows this approach: it combines *in-situ* materials with 3D printing approaches to construct habitats and other civil infrastructure needed for long-duration stays. Currently, teams of SMEs at both NASA Kennedy Space Center (KSC) and NASA Marshall Space Flight Center (MSFC) are actively studying, and developing, different approaches to make this technology viable for future missions.

The contest supported NASA's work, inviting solvers to develop additive construction systems for the Martian surface. SMEs recognized that a contest could draw input from domains and individuals with whom they usually did not collaborate—potentially having a meaningful impact on their work. As such, SMEs tailored the contest to "push the boundaries" of the problem and complement their current efforts. To do this, they formulated what problem(s) solvers would tackle, fielded solvers' questions, and judged the submitted solutions. The NASA SMEs received significant input from SMEs from Bechtel, Brick and Mortar Ventures, Caterpillar Inc., and U.S. Army Corps of Engineers (USACE), who lent their expertise despite their lack of a footprint in the space industry.

3DPH consisted of four independent challenges. Each challenge focused on different technical areas—each with its own requirements and prize awards (Vrolijk and Szajnfarber, 2021). The Design Challenge asked solvers to design architectural concepts for future habitats. In the Structural Member Challenge, solvers developed and demonstrated the performance of their printer feedstocks—equivalent to a desktop printer's ink—for the Martian surface. The Virtual Construction Challenge asked solvers to provide detailed analyses of their habitat designs. And finally, solvers autonomously printed one-third scale models of their designs—with a footprint of at least 10.33 m^2—in the Construction Challenge. These four challenges were launched across three sequential phases and offered solvers approximately $2.5 million in prizes.

As envisioned, participants in the 3DPH were primarily outsiders to the space industry. Solvers came from a variety of industries including design, architecture, 3D printing, additive manufacturing, construction, as well as the space industry. Many solvers formed a team to participate, and many teams were associated with universities or companies. Overall, the architecture and design themed challenges (Design and Virtual Construction) saw more participation than the hardware focused ones (Structural Member and Construction). We summarize relevant details in Table 2.1 below.

Table 2.1: Summary of NASA's 3DPH Contest

Phase	**Challenge**	**Total Solvers**[a]	**Winner**[b]
1	Design	167	Team of architecture professionals
2	Structural Member	8	Industry collaboration
3	Virtual Construction	18	Space architecture start-up
3	Construction	7	Construction technology company

[a] Number of solvers, be it a team or individual, that submitted a solution to at least one part of this challenge.
[b] Affiliation of solver who took home the largest prize in that challenge.

The 3DPH Challenge was our case study. It was regarded as a model contest at the time, and—later—an important success across the agency. Thus, we chose to study this unique case in-depth, which—as the literature suggests (Yin, 2009; Siggelkow, 2007)—would reveal the range of benefits that innovation contests can provide its seeker. Since the 3DPH team could best describe these benefits, we engaged with them at the contest's inception in 2015 and collected data until a year after its final prize award in 2020.

Our analysis drew on, and triangulated across, a range of data for this work. First, we interviewed 49 individuals involved with 3DPH in a semi-structured manner (Converse and Presser, 1986). Our questions were wide-ranging, and included asking whether and how the contest benefited them (and NASA), if they did not bring it up themselves. Interviewees included all NASA SMEs involved with the formulation of the problem and running the contest: the scientists and engineers tasked with developing additive construction systems for NASA at KSC and MSFC, as well as all CCP personnel involved with the 3DPH, both past and present. We also interviewed the external experts who assisted the NASA SMEs, as well as various solvers across the different phases of 3DPH. Second, we collected project documents that, contemporaneously, described the contest's goals and outcomes in detail. Finally, we also drew on our firsthand observations at various 3DPH events to corroborate the picture painted by our interviewees and archival data.

We analyzed our data for the benefits to the seeker. First, we open coded the transcribed interviews and other documentation for advantages that the contest provided to the NASA SMEs involved with planetary additive construction (Strauss and Corbin, 1990). In each case, we noted the stage in the innovation contest process and who drove that benefit. Next, we inductively formed common categories from these instances, consulting the available literature and iterating until no new categories formed (Strauss and Corbin, 1990; Miles and Huberman, 1994). Finally, we arranged our set of categories into a framework, summarizing the *who*, *what*, and *when* questions we described earlier. In our analysis, we chose to examine the breadth of benefits—instead of the frequency with which they were mentioned—to avoid obscuring potential benefits to the seeker.

2.4 Findings

2.4.1 Benefits During Formulation

Built Connections Both the SMEs and the CCP team praised the connections they made with experts in other domains during the formulation stage. Here, the contest gave them a platform to "get outside the known group of people and companies that we deal with," per one NASA subject matter expert (SME). By reaching out through their contacts—and having those individuals reach out to contacts of their own—the 3DPH team connected with companies and academics in the additive manufacturing, architecture, and construction industries. Participation in the formulation of the contest was mutually beneficial. It offered the external entities the opportunity to be a part of an emerging community, shape the trajectory of a new technology, and gauge future market opportunities. In turn, 3DPH created a platform for NASA SMEs to connect with outsiders, and dig into the overlaps between their respective industries. SMEs also noted that these connections, and the ensuing conversations, are much harder to forge via other mechanisms in NASA's toolbox; instead, "a challenge breaks that paradigm somewhat."

Reduced resource burden The external sponsors contributed their resources to 3DPH's NASA's resources needed to challenge the problem. Unlike other innovation mechanisms in their portfolio, NASA can accept external sponsorship via their contest partner. Here, the 3DPH team attracted several non-space sponsors through a common interest in additive construction. Sponsors volunteered their (civil engineering, construction, and architectural) expertise, assigning their technical staff to serve on the problem formulation team and to serve as judges. Their investments are estimated at $2 million. Here, the external experts provided the infrastructure required to host the events and test printed samples, guided the seeker towards the appropriate testing and evaluation standards, and made the problem more comprehensive than originally budgeted. Their help likely shortened the problem's total formulation time and improved the quality of the contest's results.

Acknowledged capabilities With the help of the external experts, the NASA SMEs gauged the state of the art across different industries to respond to their needs. While formulating the 3DPH problem, the (combined) formulation team surveyed how different entities within their industries could respond to NASA's additive construction needs. Here, the external experts offered their assessment of the current capabilities of their industry, and what would advance the state of the art. This information helped the NASA SMEs shape the performance criteria for 3DPH's problem: striking a balance between what NASA needed but was not yet developed and what could already be done (either by NASA or others). Per one NASA SME:

> "If [a problem is] completely feasible then there's no point in having the competition. So, you have to get to something that you're 90% can be done, but you're 10% not sure."

2.4.2 Benefits During the Solving Process

Raised visibility of technology Once 3DPH was released, it provided NASA SMEs with a conduit to communicate their needs and goals broadly. The contest promoted their work in additive construction to audiences that they "probably wouldn't have considered before," per the CCP staff. Outlets ranged from (additive) manufacturing conferences, construction tradeshows, Reddit, and other niche technology blogs. NASA SMEs were happy that the contest drummed up broad excitement: "[a contest] needs to be really inspiring and this one was. Everybody understood it and people were very excited about it." This also placed NASA, and its planetary additive construction SMEs in particular, as leaders in this emerging field.

Reduced resource burden This contest asked solvers to design *and* demonstrate their solutions, shifting costs and risks away from the seeker. It was up to the solvers to balance this burden against their strengths: drawing on their (team's) expertise, infrastructure, and funds to create a solution that worked. As each team found their own balance, they—independently—explored different kinds of solutions to the same problem. For example, a team from the construction industry leaned on their company's extensive expertise for their solution in the Structural Member Challenge. Here, they created a familiar building material in an unfamiliar setting: developing and testing Portland cement created from simulated Martian materials. In contrast, another industry team leveraged their contacts to design and test a custom thermoplastic feedstock for their printer. The CCP has estimated that solvers spent approximately \$5 million dollars on developing their submissions.

Acknowledged capabilities The formulation team received solution information via feedback from (potential) solvers prior to their submission. They received this through public requests for information during the formulation stages. NASA SMEs also received feedback via public webinars and direct (and private) questions to the formulation team. Some of this feedback questioned the feasibility of the rules, indicating that (potential) solvers could not comply with the problem as posed. Other solver feedback would ask for their blessing on a proposed solving approach, and included detailed design choices. The volume of these interactions would peak to dozens per week during each phase of the contest, giving the formulation team a detailed understanding of the solving capabilities of the crowd. In turn, the team would clarify or change the rules accordingly.

Spurred relevant development 3DPH's formulation team encouraged solvers to explore solutions that matched NASA's aims. The SMEs were, of course, very familiar with the NASA context and the Martian environment. They knew that not all solutions would, ultimately, be feasible. As such, they preferred certain design families over others. For example, SMEs were interested in using thermoplastics as a binder in their feedstocks: these would, potentially, perform better than those that used a water-based cement. Even with this knowledge, exploring the full tradespace to find the optimal feedstock would be expensive for NASA. There are a multitude of binder material, aggregate, and printing process combinations which deliver different performance results. Solvers chipped away at this issue by exploring different permutations in this class of materials; considered “a really good outcome,” per one SME.

2.4.3 Benefits When Solutions are Reviewed

Built connections NASA SMEs benefited from the breadth of the solvers who participated and strength of the ties the contest created. Teams from the design, architecture, and construction domains participated in all phases of 3DPH—industries that, traditionally, do not interact with NASA. In fact, of the 60 teams that participated, only a handful came from the space industry. These solvers also represented a range of academic, hobbyist, and industry backgrounds. The contest’s connections to non-space, commercial entities appealed to solvers with commercial aims. Their involvement signaled to those solvers that the technology was not just limited to space. Per one NASA SME, 3DPH “really represent[ed] a great way to bring in garage maker innovators, who probably aren’t out there applying for government contracts or even thinking about government work in any capacity.”

Additionally, the contest provided a platform to meaningfully interact on a shared interest: the NASA 3DPH team, sponsors, and solvers made lasting connections that endured long after the contest ended. These connections formed through informal networking during the competition, at the in-person face-offs, and at their social events. One participant described the long-term impacts of building this community, even outside of the contest:

> I would say that the friendships and business contacts that our team made came heavily from [the 3DPH social event]. . . . Even when knowing that both [our teams] were considering starting businesses around [the same topic], we had explored ways to work together, and like I said, kept in routine contact with

each other about both ideas and from a business standpoint.

Acknowledged designs and capabilities The solvers' solutions exposed NASA staff to new designs and capabilities in additive construction. First, the solutions presented new design choices *and* how those choices performed against the contest's criteria. Examples include a recipe for a thermoplastic-basalt fiber feedstock with a material strength 20+ times higher than concrete. Another team designed, and demonstrated, a feedstock that could wholly be produced on Mars using synthetic biology and in-situ resources. Overall, SMEs appreciated the variety of solutions presented by the solvers, acknowledging new designs in printing automation, robotic coordination, and configurations of the habitats.

Second, the solutions also revealed new capabilities that the SMEs did not think were possible. In the Structural Member Challenge, one team's configuration of printing system and feedstock allowed them to print horizontally—in midair—without supports. Prior to this demonstration, this capability was considered impossible; the requirements only asked participants to autonomously remove supports used to print. An SME developing NASA's planetary additive construction infrastructure acknowledged this capability as "the holy grail in 3D printing," and it informed subsequent internal development.

2.4.4 Benefits After the Prize Award

Collaborated on related projects After the contest, the NASA SMEs stayed in contact with several solvers and invited them to participate in new internal projects. 3DPH gave solvers an opportunity to demonstrate their expertise, and showed SMEs how those solvers could bolster (new) projects in their pipeline. As such, when relevant internal projects arose, SMEs formed new partnerships with these solvers, adding external capabilities to their own. In a few cases, the SMEs also referred solvers to other NASA offices with relevant projects. The multi-year follow-on projects—ranging from \$20 thousand to \$14.5 million—asked the (now former) solvers to perform trade studies and develop hardware that the NASA would test in their facilities and with their equipment. While most follow-on projects tackled different problems than what was challenged, all were broadly related to additive construction on other planets. In total, upwards of \$15 million in funding was directed to the solvers and their NASA partners directly following the contest—much, much larger than 3DPH's prize purse. The NASA partnerships transformed the solvers from ad-hoc contributors to stable partners, providing their expertise on a more traditional basis.

Raised visibility of technology Both solvers and their contest solutions raised the visibility of additive construction technology after the contest ended. For solvers, participating in—and, for some, winning—3DPH was a source of pride and further opportunity. Teams actively promoted their efforts and leveraged these towards new funding and commercial opportunities: one team praised the "avalanche of press, international museum exhibitions and speaking engagements that [3DPH]" generated for them after the contest. These activities spread the word about NASA's goals and current efforts long after the contest was over.

Additionally, the solutions helped NASA communicate its efforts to internal and external audiences. For example, the visual components of the Design Challenge solutions were "beautiful," per the CCP staff. Their use in promotional material helped the public visualize a complicated problem, and helped communicate what 3DPH asked solvers to do in subsequent phases. More broadly, the printing demonstrations in the Construction Challenge sparked serious interest to deploy this technology in the disaster relief and affordable housing sectors. Together with the CCP, the U.S. Department of Housing and Urban Development and the United Nations' UN-Habitat began exploring demonstration prints in relevant locations with 3DPH solvers. Thus, solvers, and their solutions, became strong advocates for NASA's goals and additive construction technology both inside and outside the space domain.

Absorbed designs After their review of the results, NASA SMEs absorbed several solutions into their systems and processes. Absorbing (part of) these solutions went further than recognizing that it was novel and useful. It meant directly adopting a solution to the challenge into NASA's processes, with the hope of directly improving the SMEs' existing capabilities. For example, the stellar performance of the (Phase 2) winner's feedstock prompted the NASA SMEs to procure a batch and use it in their in-house printers. Other instances included adopting one team's material processing techniques, or flying samples of solvers' feedstocks to space on NASA missions. We summarized the solutions absorbed by the planetary additive construction teams at KSC and MSFC in Table 2.2 below.

Table 2.2: 3DPH Challenge Solutions Absorbed by NASA

Challenge	**How the seeker absorbed the solvers' solutions**
Design	SMEs created a taxonomy of 98 final solutions as a reference document
Structural Member	The KSC team used a thermoplastic-based feedstock in their in-house printer, and adopted the solvers' manufacturing approach
	The MSFC team and astronauts tested a cement-based feedstock on the ISS
Virtual Construction	NASA press releases and other media products used solvers' habitat designs
Construction	The MSFC team tested samples of a thermoplastic-based feedstock in orbit
	The MSFC team and astronauts will test a cement-based feedstock on the ISS (once again)

Spurred relevant development Some former solvers continued their development of additive construction capabilities after the contest. They secured hundreds of millions of dollars in venture capital *as well as* millions of dollars in grants from the U.S. Department of Defense. One team successfully advocated for building code changes to accommodate additively constructed houses in their local jurisdiction.

While these developments happened outside the space context and independent of NASA's direction, there are spillover benefits to the seeker. Considering that (parts of) the solvers' designs were favorable to NASA's aims, further development might address uncertainties that the contest was not able to. For example, the winners of Phases 2 and 3 went on to use their thermoplastic and basalt feedstock in their terrestrial work, despite their Mars-focused origin. Exposing their material to a variety of use cases on Earth will build an understanding of how it behaves under a multitude of printing conditions. Similarly, solvers' advances in printer teleoperations and printhead path planning are equally relevant to space applications of this technology, and will inform NASA's planetary additive construction efforts. As one of our interviewees noted, until NASA was ready to launch the technology in the 2030s, the teams will "keep it alive" in their home domain.

2.4.5 Framework

Figure 2.2 summarizes the benefits of an innovation contest to its seeker. We built this framework by aligning the coded benefits to their place in the four-stage process and highlighting who drove them. Thus, this figure summarizes *what* benefits occurred *when* and *who* they stemmed from.

The figure highlights that network- *and* technology-related benefits—of which solutions were one part—appeared across all stages of the contest. Sometimes, the same kinds of benefits appeared in different parts of the process. For example, information on potential solutions flowed to the seeker in the Formulation stage *in addition* to the Solve and Review stages where this would be expected. This information helped them better understand the state of the art, and thus the bounds of what they could ask solvers to do (for the prize provided). Similarly, the seeker meaningfully expanded their network in both the Formulate and Review stages: first to organizations interested in the same subject matter, and then to solvers.

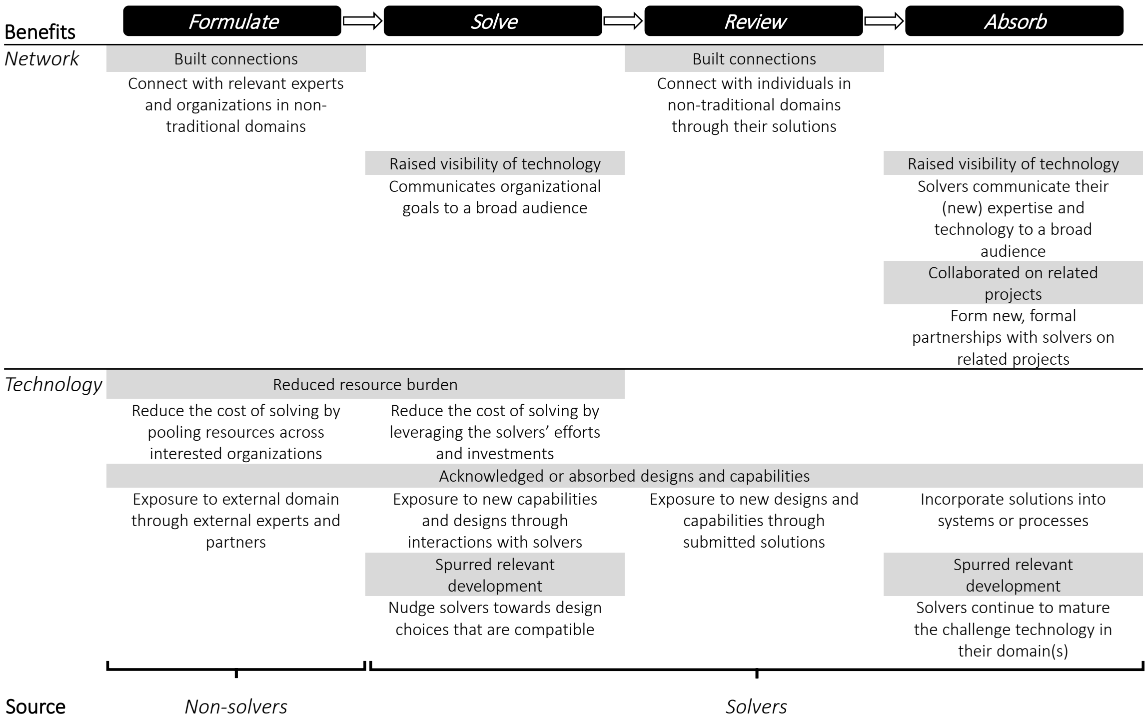

Figure 2.2: Summary of network- and technology-related benefits across the different stages of the innovation contest

The figure also highlights that the source of these benefits was not always the solvers. In the Formulation stage, the seeker received solution information from external SMEs. These companies and organizations connected with the seeker as sponsors and/or experts in distant, but relevant, domains. They meaningfully connected and expanded their respective networks through the contest. Notably, the external experts did *not* become solvers in later stages. Rather, they continued their support through e.g., facilitating the contest or judging its solutions.

2.5 Discussion

The literature has long touted the solutions as being the most important and most valuable benefit stemming from innovation contests. In this framing, scholars have focused on increasing the quality of the received solutions through e.g., selecting for specific solvers (Jeppesen and Lakhani, 2010; Acar, 2019; Szajnfarber et al., 2020; Frey et al., 2011), selecting for specific solving behavior (Bayus, 2012; Acar and van den Ende, 2016; Natalicchio et al., 2017), or adjusting the judging processes (Piezunka and Dahlander, 2015; Alexy et al., 2012). Also in line with this framing, practitioners are encouraged to get the solutions as quickly as possible; any stage besides Review is supportive at best, or a burden at worst. For example, though Paik et al. described the Formulation stage's importance in "clearly [defining] the desired outcomes and metrics" required for the solutions (2020, p. 45), they do not address any benefits during this stage despite incurring most of the contest's costs.

We caution against a narrow framing. Contest benefits are not only in support of the solutions, like connecting to diverse individuals to increase the likelihood of good solutions. Our work emphasized that innovation contests provide a range of benefits, and that these are inherently important to the seeker. Moreover, some stages can be more valuable to the seeker than its Review stage. In our case, the post-contest technology development projects—where the former solvers became NASA partners—were valued at many more times the prize awards. Additionally, most have been directly funded by NASA's wider technology efforts to sustain human presence on the Moon. This has brought additional attention across the agency, and a defined pipeline to move the solvers' current technologies to flight demonstrations. This and other examples from our case study offer a counterpoint to the literature's focus on solely obtaining solutions from solvers. Approaches and models that maintain this focus will ignore these important benefits to the seeker.

Considering our results, a different view of the solutions might be warranted. To be clear, the solutions *were* inherently important in our context. Solvers demonstrated new materials, habitat and printer designs, making a meaningful impact on the SMEs working on planetary additive construction—much like the innovation contest literature predicted. But more importantly, the other—more valuable—contest benefits would not have been possible without them. Specifically, many 3DPH solvers had no footprint or future in the space industry until their participation in the contest—they only engaged with NASA *because* they wanted to solve the contest's problem. Additionally, the solutions' performance criteria allowed the SMEs to vet the solvers' capabilities and potential fit in upcoming projects. In this view, the solutions prompted by the contest's call are a catalyst for all benefits in our framework.

For seekers, our contribution means leveraging various benefits *across* the innovation contest process. Here, two drivers stand out. First, a strong community around the contest drives the network-related benefits. Here, the CCP worked hard to foster the emerging community that shared an interest in planetary additive construction. They organized opportunities, like in-person finals and networking socials, where the solvers, sponsors, and NASA SMEs could connect informally. The connections were more than a momentary exchange of information across domain or organizational boundaries. The meaningful interactions among these individuals built strong professional and personal connections. It also helped form the collaborations between solvers and follow-on activities with the seeker. The individuals involved in the 3DPH contest formed a network of people who are "a name and a phone number, [even] sort of a family" per the CCP program manager.

Second, getting diverse—and early—input on the problem's requirements drives the later technology-related benefits. The literature contends that diverse input received through crowdsourcing can reduce the risk of entrenched, non-optimal solutions (Afuah and Tucci, 2012). Diverse input might also reduce the risk of an entrenched problem: avoiding requirements that might limit valuable solutions. 3DPH's problems were both internally meaningful and externally feasible because the formulation team included external SMEs and elicited external feedback on its requirements. These increased the likelihood of successful development by solvers, as well as useful solutions for the NASA SMEs. Additionally, these early interactions between the seeker and the outsiders allowed for informal conversations about future needs, technological and market directions, and collaboration opportunities—all under the guise of the contest.

Finally, two features of our context might impact how broadly our insights apply. Specifically, our case study centered on a government program, one that specializes in running complex innovation contests. First, a government context is more able to facilitate information sharing because of a reduced emphasis on intellectual property and competitive advantages. In our case, NASA SMEs readily shared information with solvers and external experts if it did not adversely affect the contest. Second, the complex nature of 3DPH's problems likely attracted more (large) teams, whose members had more applicable experience (see also Kay, 2011). In contrast, contests challenging simpler problems predominantly attract individuals who are much more diverse, and see their efforts as part of their hobby (Blohm et al., 2013; Lakhani et al., 2010; Szajnfarber et al., 2020). The uniqueness of this context is a double-edged sword: it enables us to capture the range of potential benefits that could be realized, but its specific insights might not apply to more common applications of innovation contests. Specifically, the above factors may very well impact the relative importance of benefits observed, but not their existence in other contexts. For example, the follow-on projects emerged as an important and valuable benefit in our contest; while their occurrence is likely more prevalent in complex contests, it is certainly a factor in others as well. We believe that our framework covers the benefit space, and provides a structure that others can modify to their specific context.

2.6 Conclusion

Innovation contests are, indeed, becoming "trendy" (McCausland, 2020, p. 61). Practitioners, as seekers, play a crucial role in their success (see also Lifshitz-Assaf, 2018; Randhawa et al., 2019; Piezunka and Dahlander, 2015; Zobel, 2017) and need better frameworks to use them effectively. As scholars, we are unpacking their core dynamics and creating insights to help their contests succeed. In this paper, we highlighted the various non-solution benefits of an innovation contest, detailing who drove them and when they occurred in the process. The results cast a new light on the value of the solutions and its role as a catalyst for other benefits.

Chapter 3—The Opportunists in Innovation Contests

Understanding Who to Attract and How to Attract Them

3.1 Introduction

Technical organizations are increasingly looking to open innovation—and innovation contests specifically—for new solutions to their problems (Chesbrough, 2017; Gustetic et al., 2015; Lakhani et al., 2013b). These activities excel at reaching and gathering input from individuals and organizations *outside* of the domain of the problem (Afuah and Tucci, 2012)—a problem-solving approach innovation scholars have long advocated for (Tushman, 1977). In competitive versions of crowdsourcing, an organization—the "seeker"—broadcasts their problem(s) to a broad audience for their input; in turn, members of the crowd—the "solvers"—compete for a prize by solving said problem(s) (Terwiesch and Xu, 2008). Both the academic literature and the popular press tout the successes of these activities (Murray et al., 2012; Lyden, 2007).

But examples of failures also exist, caused in part by too many (poorly performing) solvers (Alexy et al., 2012; Dahlander and Piezunka, 2014; di Gangi et al., 2010). As such, seekers wanting to use this tool effectively still face questions like *who to attract* and *how to attract them.* Regarding the former, Jeppesen and Lakhani's study (2010) was the first to show that certain solvers are more likely to outperform others. Specifically, those who were (somewhat) removed from the domain of the problem were more likely to win the contest (see also Poetz and Prügl, 2010; Acar and van den Ende, 2016). Since then, scholars have identified characteristics that are correlated to their performance—like familiarity with the problem (Afuah and Tucci, 2012; Szajnfarber et al., 2020). Or traits that are common among high-performing solvers—like an interest in pursuing the focal technology (Gustetic et al., 2015; Kay, 2012). Combined, these insights now paint a jumbled picture of who is more likely to be a good solver, with a high likelihood of successfully solving the seeker's problem. Regarding the latter, *none* of these studies connect their findings to the incentives needed to attract the solvers in question.

To help address this gap, we connect solver performance to contest incentives. We examine three archetypes for who the best solvers are and connect these archetypes to their related incentives. Our data consisted of 60 solver teams from complex crowdsourcing contests at NASA. The results focus on the *opportunist* archetype: solvers who intended to use the contest as an onramp to new opportunities—building a revenue stream, developing and demonstrating their technology, or establishing themselves in an industry. This archetype captured most winners in our sample compared to the others. Additionally, opportunists were uniquely incentivized by in-kind prizes and support provided by the seeker. These results enhance our understanding of innovation contests and support seekers in addressing their short- and long-term organizational goals. Below, we summarize the relevant literature and provide the results of our analysis.

3.2 Relevant Literature

3.2.1 Making Innovation Contests More Efficient

Innovation contests are an established way of reaching a broad variety of solvers. The contest's non-traditional nature and (relatively) low barriers to entry can attract individuals that normally do not interact with the seeker or the focal problem (Szajnfarber et al., 2020; Gustetic et al., 2015). Specifically, many participating solvers might stem from very different domains and possess expertise and (firsthand) knowledge that the seeker does not (Afuah and Tucci, 2012; Poetz and Schreier, 2012; Franke et al., 2013; Jeppesen and Lakhani, 2010). Thus, the innovation contest can be a conduit to access relevant knowledge from a broad range of domains through the participation of outsiders.

However, the breadth and volume of solvers—and their submissions—can also be detrimental to the contest outcomes. Participants sometimes number in the tens of thousands or more, with as many submissions (Alexy et al., 2012; Bjelland and Wood, 2008). Reviewing and selecting solutions is a daunting task, especially when the seeker needs to translate the solvers' solution knowledge into their domain (Ruiz et al., 2020; Piezunka and Dahlander, 2015). The seeker is simply "overwhelmed," and good, but unfamiliar, ideas may fall through the cracks (Blohm et al., 2013, p. 200). Thus, the seeker risks negating the contest's broad search benefits.

To address this gap, scholars have tried to make the contest process more efficient while still reaping its benefits. These efforts fall under two approaches. The first focuses on identifying potentially good solutions. These are likely to address the seeker's need, but some might not seem familiar to the seeker. Strategies include spreading the burden of reviewing the solutions, allowing others to characterize (Westerski et al., 2013), rate (Hoornaert et al., 2017; Jensen et al., 2014), or provide feedback on the solutions (Huang et al., 2014; Seidel and Langner, 2015). The seeker may also limit the number of submissions to make the review process easier (see, e.g., Piezunka and Dahlander, 2015). The second approach focuses on identifying potentially good solvers. They are likely to perform well in the contest. Strategies that follow this approach characterize solvers by traits that increase their likelihood of submitting high-performing solutions and useful knowledge (see, e.g., Jeppesen and Lakhani, 2010; Szajnfarber et al., 2020; Franke et al., 2013; Acar and van den Ende, 2016). Both approaches aim to improve the outcomes of the contest, but differ in their implementation. Specifically, shaping the contest and its problem to attract those solvers requires more planning on the part of the seeker. And while various studies have explored the practical aspects of identifying good solutions, few have examined how seekers can implement the insights to target good solvers.

3.2.2 Who Should Contests Attract?

Our work informs the solver-focused approach. Below, we summarize three perspectives on who the best solvers are[1]. Each describes how possessing a particular feature makes that solver's success more likely than those who do not. The features span the solvers' home domain or industry, familiarity with the problem or topic, or planned technological trajectory. We name the resulting solver archetypes *distant solver*, *peak neighbor*, and *opportunist*, respectively.

First, the *distant solvers.* This view posits that good solvers are not from the same domain—or industry—as the problem they are solving (Jeppesen and Lakhani, 2010; Schuhmacher and Kuester, 2012; Zhu et al., 2017; Poetz and Schreier, 2012; Acar and van den Ende, 2016). Rather, these individuals stem from its margins, or come from other domains entirely (Franke et al., 2013). This archetype succeeds because, unlike the domain's experts, they are less likely to be burdened by cognitive entrenchment or fixation on a dominant design (Dane, 2010; Jansson and Smith, 1991).

Second, the *peak neighbors.* In their paper, Afuah and Tucci described good solvers as being "close to the highest peak" on the solution landscape, so "they do not have to go outside their immediate knowledge neighborhood." (Afuah and Tucci, 2012, p. 360). Their problem-solving strength rests on their proximity to a good—or the best—solution, where little searching is needed to deliver this solution to the seeker (Lakhani et al., 2007; Magnusson, 2009; Frey et al., 2011). The contest helps the seeker find experts they did not previously know about (Szajnfarber and Vrolijk, 2018; Szajnfarber et al., 2020).

Lastly, the *opportunists.* Practitioners and scholars have observed (some) good

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[1] Categorizations of culture (Chua et al., 2015), gender (Jeppesen and Lakhani, 2010), or intrinsic motivations (Acar, 2019) may also predict contest success. However, our solver data consists of both individuals and teams. This makes a coherent measurement of these constructs difficult for our unit of analysis, and less generalizable outside of contests with exclusively individual solvers.

solvers pursuing opportunities in the seeker's domain after the contest ends—with some even working for the seeker (Gustetic et al., 2015; Kay, 2011). They see the problem—and their solution—as a worthy, long-term (commercial) pursuit. These solvers might realize this before, during, or after the contest. This pivot mirrors the trajectory of some innovators described by the user-innovation literature (von Hippel, 2005): realizing that they might fill a gap in the market, some users commercialize a solution initially designed to address their own needs (Shah and Tripsas, 2007, 2016). As such, the opportunist's view distinguishes between solvers' (intended) trajectory. Specifically, good solvers use the contest to seize other opportunities and accomplish their existing goals. Their problem-solving strength may lie in their ability to foresee gaps in current solutions or approaches that others do not (Lüthje and Herstatt, 2004; von Hippel, 1986). With their intended long-term presence, the opportunists' strength may also lie in their ability to marshal (knowledge and financial) resources to solve the problem (Kay, 2012).

3.2.3 How to Attract Them?

While knowing *who to attract* might be the first question to tackle, equally important is knowing *how to attract* those solvers. To date, there have been several studies digging into why solvers participate in innovation contests. One perspective draws on the psychology literature to trace the solvers' *motivations* (see, e.g., Deci and Ryan, 2000; Ryan and Deci, 2000). Studies under this umbrella focus on why solvers would decide to participate in these contests. They describe intrinsic (e.g., having fun) and extrinsic (e.g., winning a prize) motivations as strong determinants for participation and quality of solutions (Frey et al., 2011; Acar, 2019; Mack and Landau, 2015). However, when the focus is on solvers' (intangible) motivations, these insights lack the resolution to be actionable: what incentives—and at what levels—should the seeker set to match those motivations?

Another perspective flips this around: it traces the influence of (different) prize *incentives* on solvers' participation. It draws on the literature on tournaments and the efficiency of incentives to motivate the desired effort in a contest environment (Taylor, 1995; Fullerton et al., 1999; Shavell and van Ypersele, 2001). This view focuses on the lever(s) that the seeker can use to draw participants to the contest. Here, studies specify the (levels of) monetary and (kinds of) non-monetary incentives that the seeker can implement (Murray et al., 2012; Kay, 2011; Ihl et al., 2019; Davis and Davis, 2004). Some even specify how one might be more successful in inducing innovative behavior Brunt et al. (2012). But these studies rarely, if ever, provide insights on *who* responds to those incentives or how to attract winners.

As such, there is a gap between who seekers should be targeting and how they should set their prize(s) to incentivize their participation. This study bridges that gap, connecting solver archetypes to relevant incentives.

3.3 Methods, Setting, and Data

Our understanding of innovation contests generally, and the dynamics of solvers within them specifically, is still at a stage where qualitative data and analysis methods are required to identify and capture the dynamics relevant to our question (Eisenhardt et al., 2016; Szajnfarber and Gralla, 2017). Following the literature's guidance, we selected a setting where we could collect the relevant data and analyze them accordingly.

This setting is CCP, the agency's flagship for challenging complex, crowdsourcing contests. NASA's technology road maps inform CCP's contests; NASA SMEs—sometimes aided by external SMEs from other domains—formulate them to be complimentary of NASA's ongoing efforts (Vrolijk et al., 2022). We observed seven active contests within this portfolio, summarized in Table 3.1. Each contest had its own technical focus, solver base, and relevant SMEs. The prize purses ranged from $50k

Table 3.1: Overview of Contests and their Solvers

Contest	**Prize ($k)**[a]	**Stages**[b]	**Solvers**[c]	**Focus**
Mars Ascent Vehicle	50	1	10	Automated loading and launching of Mars samples
Vascular Tissue	500	1	1	Growing and sustaining human tissue
Space Robotics	1,000	1	3	Simulating robot operations on Mars
CO2 to Glucose	1,000	1	5	Converting CO2 into bio-feedstocks
Sample Return Robot	1,500	2	13	Automated locating and collecting of Mars samples
3D Printed Habitat	2,450	9	22	Additive construction of habitats on Mars
CubeQuest	5,500	4	6	Deploying miniature satellites in deep space

[a] Total prize pot available per contest.
[b] Prize awards per contest captured within this data set.
[c] Number of solvers within this data set.

to $5.5M and were divided into smaller sub-contests—or stages—with their own prize award and ranking. Solvers, participating solo or as a team, stemmed from academic, industry, and hobbyist backgrounds. In short, the nature of the contests in the CCP portfolio, combined with the variation of solvers in each contest, provided us with an ideal setting to explore our research question.

The data for our study consisted of 37 hours of semi-structured interviews with 60 solver teams (Converse and Presser, 1986), the unit of analysis for this work. Whether a team consisted of one or multiple people, we asked their representative questions on their participation. Our questions covered their team's demographics and experiences, reasons for entering the contest, the basis for their solution and its relevance to their work outside the contest, and any future plans. These broad questions allowed the representatives to freely explain who they were, and elaborate on their relationship with the contest and its subject matter.

We applied a combination of deductive and inductive coding to the transcripts of these interviews (Miles and Huberman, 1994). First, we deductively coded all teams in our sample according to the three archetypes we described in the previous section.

We explain these measures.

Distant solver To identify distant solvers in our sample, we examined teams' focal industry before the contest. Taking the seeker's perspective, we coded teams with substantive ties to the space industry as *local.* In these cases, team members had previous or current experience in the space industry or if the organization was engaged in space-related activities. Otherwise, we coded the team as *distant.*

Peak neighbor We identified teams as peak neighbors if they described the team's familiarity with the problem posed or the technology being challenged in the contest. These solvers mentioned the related projects they worked on, past or current, and described how these experiences informed their participation—we coded them as *peak.* In contrast, we coded solvers as *valley* if they indicated that the subject matter was new to them or did not comment on their familiarity with the problem.

Opportunist We coded teams as opportunists if they entered the contest to explore new technical opportunities. They would describe the contest as a springboard for this exploration, impacting their careers, technological, and organizational trajectories. We coded these teams as *opportunists.* If they stated that their focus on this subject matter would be limited to this contest, or did not mention any such plans, we coded them as *transactors.*

We then inductively coded the teams' transcripts to uncover the incentives that motivated them to participate (Strauss and Corbin, 1990). To do this, we first identified text fragments that described what attracted them to the contest(s). Then, we organized these fragments into common, higher-order categories. We iterated through these data and adjusted the categories until we reached a stable set. Within this set, we also noted that some incentives were more closely tied to the space industry than others (i.e., networking in the space domain, recognition by space SMEs, and accessing the seeker's infrastructure and services). With these eight categories formed, we coded each team for the relevant incentive categories. The categories, and example quotations by teams' representatives, appear in Table 3.2 below.

3.4 Findings

Our findings connected the most successful type of solver to the incentives that consistently attract them. Opportunists saw the contest as a springboard to future technical opportunities, and participated to put themselves on this path. The opportunist archetype captured most of the winners in our sample, matching our data more closely than either peak neighbor or distant solver. Additionally, opportunists were the only archetype reliably motivated by the seeker's in-kind incentives to participate, Thus, by gearing the contest to incentivize this archetype, the seeker may more reliably incentivize good solvers. We explain these findings below.

3.4.1 Describing the Opportunists in our Data

Whether they stemmed from academic, industry, or hobbyist backgrounds, opportunists' intended trajectory was the most important distinguishing characteristic for the contests' finalists. They viewed the contest as the start of a new pursuit instead of a temporary undertaking: the contest is a springboard to new opportunities. Through their participation, they intended to build a revenue or income stream, further develop and demonstrate a technology they were interested in, or establish themselves within the industry they were targeting. One or more of these pursuits were crucial parts of their reasoning to participate. In some cases, these even influenced how solvers approached the problem.

In the example below, a team in the CubeQuest Challenge describes how they approached the design of their team's CubeSat—optimizing for their pursuit *after* the contest, not (only) the contest's rules.

> We are, from the start, viewing this [contest] as a commercial activity. Basically,

Table 3.2: Incentives Categories Coded in our Data

Incentive category[a]	**Teams in Sample**[b]	**Key Terms**	**Example quotation**
Networking in space domain	5	contacts with NASA, stakeholders	"Yeah, well we [participated] mainly because we were interested in getting some contacts with NASA."
Recognition from space SMEs	8	demonstrate, showcase	"[W]e really have robust material engineering innovation. Which I think is much more relevant to NASA at a practical level. I think that our recipe could be something that they can take on the Moon, on Mars, whatever. I think it's probably something they don't know, haven't thought about, and [yet] is extremely relevant."
Seeker's infrastructure and services	4	access, do for us	"What, in effect, the [challenges] are doing for us is they're providing another example of a tough room. People that are willing to go through and review our designs."
Challenge structure	6	deadlines, goals	"We're doing the competition because it aligns . . . The competition helps us because it has rigid deadlines. Helps us to pull everything together to meet the deadlines. Helps to move the research a bit faster."
Money	16	prize money, dollars	"Then I said [to my teammate], 'The top prize is like 1.5 million dollars.' This is on Skype and he's typing, and there's a pause and then he says, 'Oh really?' And then after that it was like, 'Yeah, we should do this."'
Networking in non-space domain	3	interaction, network	"So as I said, the challenge, I'm not really looking at it as an end product, more like an avenue for interaction, going to these conferences, see the latest trend. I look at these challenges like more of a network rather than funding."
Publicity	4	publicity, branding	"We thought we could get some publicity."
Recognition from non-space SMEs	7	seen as experts, prestige	"We hope to publish our results [in a non-space journal] in some form."

[a] The first three incentives tie closely to the space industry, the next five do not.

[b] Count of the number of teams that mentioned this incentive category (n = 60 teams).

> what we're trying to go off and do is, from the start, design something that makes economic sense to fly.

3.4.2 Opportunists Outperformed other Solver Archetypes

Our coding of teams in our sample revealed that the opportunist archetype identified more winners than the other two. Table 3.4 summarizes the number of teams coded according to each archetype, how many took first prize in the different stages, and how many won a lesser prize. In it, we tested each theoretical perspective against each other: we compared how well each archetype identified the solvers who won any prize within our sample. Here, 12 opportunists won (out of 18 winners), and six opportunists took home lesser prizes (out of a total of eight finalists)—neither the distant solver nor peak neighbor archetypes identified as many awardees in our data.

3.4.3 In-kind Incentives Attracted Opportunists

Next, we analyzed how different incentives motivated the different archetypes. In Table 3.6, we matched the incentives categories revealed by our coding with the archetypes that describe them as motivators for their participation. Each entry in the table describes which solver type(s) per archetype mentioned a particular incentive. For example, when comparing peak and valley neighbors, only the latter described networking in a non-space domain as an incentive to participate. In contrast, cells with a "both" entry indicate that both solver types within that view mentioned that incentive.

Once again, the opportunist archetype stood out among the others. The incentives hardly differed between solver types in the peak neighbor and distant solver characterizations: both good and poor solvers were attracted equally (with one exception). This is not the case for opportunists. They consistently mentioned three incentives that their counterparts did not. First, networking with NASA SMEs who work in the problem's topic area. The opportunists described how they participated "mainly

Table 3.4: Three Solver Archetypes and their Performance Across NASA's Centennial Challenges

Archetype	**Teams in sample**[a]	**Winners**[b]	**Finalists**[c]	**Example quotation**
Distant solver	34	9	5	"So, we always wanted to get into aerospace, slash [International] Space Station use, slash Mars use. NASA's CO2 conversion challenge— The timing was just really good because they released the CO2 conversion challenge when we already knew we wanted to get into aerospace." "I have an amateur slash fan interest in space exploration and sci-fi. All of those. It's just something that's interesting to me. I like thinking about new technology and new applications of that." "As an architect, I participated in many different architectural competitions. This is a very different one: out of the box and out of the world with a very good cause."
Peak neighbor	21	6	2	"I was working on this before NASA even had this competition. I was working on houses on Mars and when NASA launched this thing, I said, 'Actually this is pretty close to what I'm doing anyway. It would be really cool to submit."' "A common friend of ours had shown up to the third competition and seen what was going on and figured out that we had a pretty decent shot at winning a million dollars. And he had a robot in his closet that we could use as a platform that they had worked on during their senior project here." "And then we saw this NASA contest about 3D printed habitats for Mars, and we thought that this is right up our alley. Exactly what we're exploring as well."
Opportunist	32	12	6	"Initially, we were undertaking some research that had to do with electrolysis propulsion. . . . When this prize opportunity opened up, we realized that that would be a way to demonstrate the technology that we had already been working on. . . . For us, it helps achieve research goals." "We hadn't done anything so far. But the whole point [of participating] was to make a CubeSat— The schematics for a CubeSat that would be [our university's] designed standard that would even further make it easier and cheaper to make CubeSat for universities and companies." "I try to do construction for extreme environments. And final goal is space construction. . . . So everything is the same construction, but in extreme environments. . . . I got the dream to make the house on the Moon."

[a] Out of 60 teams in our sample. [b] Out of 18 solvers who won first prize. [c] Out of 8 solvers who won a lesser prize.

because we were interested in getting some contacts with NASA." Here, the contest was a reliable way to meet key people in an industry they were interested in "without cold calls." Second, recognition by NASA SMEs for their technical achievements. Assuming that they would create a strong submission, the opportunists believed the contest could help them "[get] our name out there with the community [and be] a part of that whole group." They could then leverage that recognition within the domain after the contest. Lastly, accessing NASA's infrastructure or services. As a large technical organization, NASA possesses a range of world-class infrastructure and expertise that surpass those possessed by individual solvers. The costs of accessing these commercially could range in the millions of dollars if they are available outside of NASA. Nevertheless, the contest provided solvers (a chance to) access to NASA's infrastructure and expertise—which opportunists strongly desired.

For example, one team—a CubeSat start-up company—described how a "tough room" of NASA SMEs provided valuable, expert feedback on their designs that were intended for commercial markets after the contest. And while the contest's "[prize] money is somewhat motivating," another team described how a chance to fly to the moon was "the number one motivator" for them. As they explained below, that opportunity was unique and worth much more than the dollar value of the prize money.

> [T]he opportunity to launch our spacecraft to lunar orbit itself has far more value than the dollar amount we would expect to bring in via the prize. ... I don't think it's possible to buy a launch on [NASA's Space Launch System rocket], and if you could, I don't think it would be $200k, it would be way more than that.

In short, the opportunist archetype was a meaningful distinction among solvers in complex innovation contests. The solvers we categorized as opportunists were more likely to be winners than the other archetypes of good solvers in the literature. Additionally, they were the only distinction between solvers that displayed a unique and meaningful difference in their incentives. Specifically, they were incentivized by in-kind support and prizes provided by the seeker. These findings shed new light on who good solvers are and provide a path for future seekers to narrowly incentivize them to participate. We discuss these below.

Table 3.6: Incentives Across Different Solver Archetypes

Incentive category	**Solver archetype**		
	Local or Distant Solver?	*Peak or Valley Neighbor?*	*Opportunist or Transactor?*
Networking in space domain	both	both	Opportunist
Recognition from space SMEs	both	both	Opportunist
Seeker's infrastructure and services	both	both	Opportunist
Challenge structure	both	both	both
Money	both	both	both
Networking in non-space domain	both	Valley	both
Publicity	both	both	both
Recognition from non-space SMEs	both	both	both

Notes: In this table, "both" entries are grayed out for clarity.

3.5 Discussion

Organizations are increasingly launching innovation contests to support their existing innovation activities (McCausland, 2020). At the same time, they are also ramping up the complexity of the problems they challenge (Gustetic et al., 2018; Lakhani et al., 2013b), which pressures the seeker to run an efficient contest. Understanding how we can shape the contest to better serve the seeker's goals will allow them to put this tool to good use. In this vein, our study describes one lever to accomplish this shaping. Its findings link the contest's incentives and the kind of solver who is more likely to win, thereby providing useful knowledge. These results enhance our understanding of innovation contests and support practitioners looking to shape their next contest and industry.

3.5.1 Implications for Complex Innovation Contests

First, our study addresses calls to further understand the solvers in the innovation contest (Bogers et al., 2017). In particular, our study addresses what happens to these solvers "after and beyond crowdsourcing" (West and Bogers, 2017, p. 45). Drawing on the literature, we compared three solver archetypes of good solvers: three different characterizations of those who would be more likely to succeed in a contest. The findings show one archetype identified more winners than the others: the opportunist. These solvers view the contest as a springboard to new, related opportunities. Because of the alignment between their long-term pursuits and the contest, they view their participation as pivotal to their future rather than transactional. While this archetype has not previously been articulated, examples of their successes are described in the literature. For example, the winner of the Northrup-Grumman Lunar Lander Challenge "was organized as a small rocketry and propulsion start-up that focused its activities to pursue the prize challenge" (Kay, 2011, p. 372).

These findings also present a new lens on the efficiency of the prize purse to attract solvers. Tournament theory has long searched for the appropriate, absolute value of the monetary prize that incentivizes the desired behavior (see, e.g., Fullerton et al., 1999; Ehrenberg and Bognanno, 1990). Instead, we show that prizes that carry a high value for certain solvers, but are comparatively cheap for the organization, can also produce useful outcomes. These insights form the basis for a prize *portfolio* instead of a prize pot: a mix of monetary and in-kind incentives that balances the seeker's cost of each, their organizational goals, and the desired solver turn-out.

Second, the "springboard" view of the contest challenges the perception that the contest is a temporary pursuit for the solvers. Solvers created significant, lasting organizational structures, and they pivoted to the contest's topic for the long term. The former mirrored the behavior of firms as viewed through the lens of the knowledge-based theory of the firm. In this view, a firm as a problem-solving or knowledge-producing entity aims to "efficiently generate knowledge and capability" (Nickerson and Zenger, 2004, p. 617). They form to create knowledge to solve a problem (Kogut and Zander, 1993; Nonaka, 1994)—consolidating the assets and resources needed to do so successfully. Similarly, teams gathered the right expertise and raised enough funds to address the contest problem in our context. This usually meant expanding their team and formalizing their organizational structure—much like a traditional firm would do. For example, one participant in the 3DPH Challenge described how they got involved with their team: "I probably wouldn't be involved at all [in additive construction] without this competition. They hired me. My background is in 3D printing entirely, and they hired me specifically for this."

The latter challenged the view of (all) solvers interested in short-term or low-intensity engagement with the contest's topic. The study of user-entrepreneurs showed that their relationship with the solution to their needs is not static (Shah and Tripsas, 2007). Similarly, this work shows the long-term relationship between solvers and their solutions: opportunists used their efforts in the contest as a catalyst for long-term change—whether that was accelerating their current pursuits or opening new ones. These findings limit how much we can define crowdsourcing solvers as "gig-workers" (see, e.g., Szajnfarber et al., 2020; Shergadwala et al., 2020). This label does not apply to opportunists: they are not completing similar tasks for a chance at a (monetary) prize. Rather, their long-term trajectories matter for their participation and the outcomes of the contest.

Third, we show that seekers can selectively incentivize different solver archetypes using in-kind incentives. All solvers are not equally attracted to the same incentives, contrasting with the picture painted by the other archetypes described by the literature. Instead, this work clarifies this distinction through the opportunist's archetype—they can be selectively targeted using the contest's prize(s). Opportunists, and *only* opportunists, were attracted to the specific in-kind incentives offered by the seeker.

Once again, their long-term trajectories made these kinds of incentives hugely valuable to their pursuits. By clarifying this relationship, the seeker can more precisely influence who will show up to solve the contest problem.

Chapter 4—Let's Meet Somewhere in the Middle

How Outsiders Reformulate Problems to Bridge Distant Domains and Create Useful Solutions

4.1 Introduction

Problem-solving, which is core to an organization's success (Nickerson and Zenger, 2004; Nonaka, 1994; Nonaka and von Krogh, 2009), is undergoing an important shift. More and more, private and public organizations are beginning to recognize the limits of solving by internal experts (Chesbrough, 2003; von Hippel, 2017). In particular, experts can be affected by cognitive entrenchment (Dane, 2010). This means they are less able to view their problems from different perspectives (Hinds, 1999), they have difficulty adapting to changes in known problems (Cañas et al., 2003), and they can rely heavily on known approaches or solutions instead of better (but unfamiliar) ones (Bilalić et al., 2008; Lovett and Anderson, 1996). As a result, organizations are shifting away from solely internal, expert-driven processes. Instead, they are increasingly using Open Innovation (OI) mechanisms to look for innovative outsiders (Chesbrough and Di Minin, 2014; Enkel et al., 2020). Studies estimate that between 4% and 7% of the population engage in innovative behavior (de Jong, 2016; von Hippel et al., 2012), based on their own needs, perceptions, and local knowledge (von Hippel, 2017). This implies a pool of millions of individuals who spend billions of dollars to create innovative products and services (von Hippel et al., 2011). OI provides an avenue for organizations to tap into this underutilized source of innovation.

The strength of OI, particularly its broadcast search mechanism, rests on outsiders with expertise that differs from the organization's—termed *distant* expertise (Jeppesen and Lakhani, 2010; Terwiesch and Xu, 2008). By broadcasting the problem widely, the organization—the solution-*seeker*—shares its core problem with anyone willing and able to solve it. Thus, the problem-*solvers* can originate outside the seeker's network or even domain. For example, determining a ship's longitudinal position in the Longitude at Sea challenge of 1714 was widely regarded as an astronomical problem (Sobel, 2005; Spencer, 2012). Even Sir Isaac Newton predicted that an astronomer would take the prize. However, astronomy-based approaches failed to make any progress over decades. Instead, John Harrison—a clockmaker—saw the problem as replacing a clock's pendulum system with something less susceptible to a boat's sway (Spencer, 2012). His approach yielded the marine chronometer—a novel solution that would revolutionize ship-based navigation.

A broadcast search unlocks knowledge and associated solving processes readily available to the distant solvers but otherwise inaccessible to the organization (Afuah and Tucci, 2012). These individuals may not know the specifics of the problem or typical solving approaches. Instead, they possess deep expertise in their own right (Afuah and Tucci, 2012; Szajnfarber et al., 2020). Faced with the seeker's problem, solvers formulate the problem through their unique perceptions and experiences (Lüthje et al., 2005; Shah and Tripsas, 2007) and apply knowledge as informed by their background (Franke et al., 2013; Jeppesen and Lakhani, 2010). Distant solver input can provide significant benefits to the seeker (Vrolijk et al., 2022). For example, scholars have theorized how the application of distant knowledge can unstick domain experts (Dane, 2010; Bilalić et al., 2008; Jansson and Smith, 1991). Solvers of this type have also identified new and productive solving approaches that can progress stubborn problems (Lifshitz-Assaf, 2018; Franke et al., 2013). And, as expected, distant solvers have provided valuable, frame-breaking solutions in industries ranging from space (Gustetic et al., 2015), to electric vehicles (MacCormack et al., 2013), to biotechnology (Lakhani et al., 2013a).

However, despite numerous successes, the broadcast mechanism relies heavily on serendipity. It is difficult to generate these outcomes systematically as the features that make distant expertise so valuable also make the process nearly impossible to direct. Usually, for a solver to innovate on an out-of-domain problem, they have to find enough meaning in a solution to invest the effort into creating it (Hienerth, 2006; Lüthje et al., 2005)—e.g., hacking an off-the-shelf glucose monitor to remotely track their child's health (von Hippel, 2017). To find these distant experts for any given problem, existing theory has relied on a large pool of solvers—and, accordingly, many submissions—to find those matches (e.g., Szajnfarber and Vrolijk, 2018). However, studies have shown the pitfalls of searching for the proverbial needle in the haystack in this solution set (Piezunka and Dahlander, 2015; Alexy et al., 2013)—one that might not even be there (Goldenberg, 2011). As such, making distant input a part of an organization's innovation toolkit will require more theory and processes to facilitate the matching of internal problems with distant solvers (and their valuable solutions).

We contend that addressing this serendipity requires a more complete understanding of the problem formulation process. So far, the broadcast mechanism conceptualizes this process as an arms-length hand-off of an organization's problem to potential solvers. It further assumes that qualified solvers will then self-identify and solve the problem as formulated. However, when the organization's internal experts formulate the problem, they risk narrowly sticking to their view of it. And with that, they are more likely to preclude the distant experts who might see the problem differently: they will not self-identify in that formulation.

Instead, we offer a new conceptualization of this process. We see formulation as a bridge, where solvers continue the process begun by the seeker's formulation (and solving). This view emphasizes the value of the seeker's (sufficiently) open-ended formulation. It also highlights the corresponding need to take notice of solutions that might appear different (and initially unsuitable).

We conducted an in-depth case study to explore the concept of *the formulation bridge*. Our research setting is a participatory technology assessment of a NASA planetary defense mission by non-aerospace outsiders. The setting provided a unique opportunity to observe the complete problem-solving cycle: the seeker's formulation; the solvers' problem interpretation and solution development; and the seeker's interpretation and eventual use of the results. Moreover, the problem's formulation was more open-ended than is typical because of NASA's intent to only engage with distant solvers. This allowed us to examine the implications of a broad formulation on the solving process. Our analysis revealed that, indeed, that broader formulation by the seeker enabled problem (re)formulation *by the solvers*, which in turn was critical to enabling solvers to leverage their knowledge productively. At the same time, it was hard for the seeker to value solutions to reformulated problems that used solvers' local knowledge. As a result, correctly valuing the solutions appears to be related to rich information exchange between seekers and solvers, a necessary aspect of the formulation bridge. The findings offer important guidance for how technical managers can leverage OI targeted at distant solvers, both in terms of how problems are framed and also how the evaluation process is structured.

4.2 Literature Review

The literature is full of examples of distant contributors providing unique and valuable solutions to solve problems important to them (e.g., von Hippel, 2017; Chesbrough, 2006; Howe, 2006). For example, the inventor of the Camelbak drinking system was an Emergency Medical Technician (EMT) who participated in extremely hot weather bike races (Felton, 2013). He needed a way to stay hydrated while keeping his hands on the wheel. To solve his problem, he drew on his experiences and fashioned a hands-free hydration system using items readily available to him: an IV bag, surgical tubing, a tube sock, a clothespin, and his t-shirt (Antons and Piller, 2014; Felton, 2013). While his solution focused on his specific problem, it has also proven valuable to many others (Chartrand, 2003). Similarly, an avid mountain biker with a human movement science day job identified the need for a bike frame design to adapt to different riding conditions. They drew on their medical experience to design this new frame (Lüthje et al., 2005). And one of the highest performers in Netflix's algorithm challenge was produced by a management consultant. He identified the importance of psychological factors in formulating the matching problem. The combination of computer science with psychology in his algorithm proved highly effective in the challenge (MacCormack et al., 2012; Ellenberg, 2008).

How do individuals make important contributions to a distant domain? In each of the previous examples, the distant solver drew on their own—*local*—knowledge to contribute to the focal domain. In some cases, they also solved a problem that they formulated locally. The examples also show that their approach can produce useful products. However, they might look and operate quite differently from existing models and appeal to new or different markets (Hienerth, 2006; Poetz and Schreier, 2012). Because of this, traditional players might have trouble recognizing the solvers' contributions as useful (Shah and Tripsas, 2007; Baldwin et al., 2006). In the sections below, we unpack each of these concepts—local knowledge, local formulation, and information transfer—and use them to build our model of problem formulation across domain boundaries.

4.2.1 Knowledge and Distance

The crowdsourcing literature often frames individuals in the crowd as novices or hobbyists, but this is a misleading picture. Many of these so-called outsiders are, in fact, experts in fields that differ from the seeker's (Szajnfarber et al., 2020; Poetz and Schreier, 2012). As experts, they possess large and interconnected knowledge structures of their domain of expertise (Fiske and Taylor, 1991). When faced with a problem in their domain, they tap into that structure to effectively and efficiently solve it (Harris, 1994; Bedard and Chi, 1992).

But experts *also* use their knowledge structure to make sense of distant problems (Ericsson and Charness, 1994; Dane, 2010). Generally, these individuals are more likely to draw on knowledge based on their background (Dunbar, 1998; Schweisfurth, 2017) or what is (easily) available to them (Baer et al., 2013; Katila and Ahuja, 2002; von Hippel, 1994). As a result, the knowledge that distant solvers draw on will be different than that of the organization's experts (Afuah and Tucci, 2012), shedding new light on old problems. We see this in the distant solver success stories above. In the Camelbak story, it took an EMT to take his IV bag and repurpose it as a water bottle for biking: the solver addressed the problem in a new way by applying knowledge that was local to them (and distant to the seeking organization). Thus, the novelty in distant solutions stemmed from the relative difference in expertise and perspective.

4.2.2 Problem (Re)formulation and Distance

The influence of a solver's distance is not limited to what knowledge they use to solve a problem. It also influences how they approach—or formulate—a problem (Kaplan and Tripsas, 2008; Wynne, 1992). When someone formulates a problem, it is transformed from an ill-defined problem into a well-defined one (Simon, 1955), ready to solve through known methods. Scholars across multiple disciplines have theorized about the formulation process under constructs like sensemaking and framing as well as formulating (e.g., Mitroff and Featheringham, 1974; Volkema, 1995; Gralla et al., 2016; Wright et al., 2015). These studies all agree: how the problem is formulated is critical to solving because it affects which solving processes are applied. Different individuals may see the same problem differently based on their differing knowledge structures (Johnson-Laird, 1983). Thus, they will likely formulate it to reflect their perspectives and experiences, or in a way that they know how to solve (Franke et al., 2013; Shane, 2000; Volkema, 1983).

We see a compelling example of this contrast in NASA's Astronaut Glove Challenge. The challenge aimed to reduce the stiffness of astronaut gloves which limited their ability to work with tools. NASA's formulation of the problem emphasized the pressure difference between the inside of an astronaut's spacesuit and the vacuum of space (NASA Centennial Challenges, 2009). However, the eventual challenge winner, Peter Homer—an unemployed engineer and garage tinkerer at the time—viewed the problem differently. He described it to the New York Times at the time (Hitt, 2007, para.45):

> "'Problem solving and invention are greatly simplified when you're asking the right question,' Homer said from his worktable, 'so the problem that I determined needed solving is how to constrain something while at the same time allow it to move.'"

This reformulation of the original problem made his knowledge of sewing boat sails, acquired through a previous job, relevant to the problem. Specifically, he designed a fabric wrapping pattern that facilitated bending across the astronaut's knuckles (Homer, 2008). Peter took home first place both times the Astronaut Glove Challenge was held.

4.2.3 The Challenge at the Hand-off Between Domains

While we have emphasized the benefits of distance between seeker and solvers, it is also important to recognize the challenge of connecting their distant perspectives. Previously, scholars have noted that transferring of the information is costly and hard (von Hippel, 1994), that individuals' correct assumptions in one domain may no longer hold when transferred to another (Carlile, 2004), and that individuals will pay less attention to information that does not match their expertise (Haas et al., 2015). These difficulties arise when exchanging information between individuals of different domains within the *same* organization (e.g., Allen, 1977; Tushman, 1977; Carlile, 2002).

Exchanging information across *both* organizational and domain boundaries is even harder. It can be difficult to recognize whether something is useful when it is not part of one's organization, nor framed in one's domain (e.g., Collins and Evans, 2002; Cecil et al., 1991; Cohen and Levinthal, 1990). And the amount of information used to transfer this knowledge can make this worse. For example, experts use shared shorthands to communicate rich information efficiently (Carlile, 2004)—sometimes referred to as jargon (Kossiakoff et al., 2011; Broniatowski and Magee, 2012). However, when spanning domains and organizations, these shorthands—lacking further explanation—can severely impede understanding between individuals. And when individuals cannot, or will not, exchange information across these boundaries, the consequences to life and property can be dire (e.g., Wynne, 1989).

While the amount of information transfer has not received much scholarly attention, it is an important factor in the crowdsourcing context. In their case study on Dell's IdeaStorm platform, di Gangi et al. describe how the shorthand used by participants in their contributions gave reviewers "little information or direction to act on," and required additional effort to unpack the contributions' technical meaning (di Gangi et al., 2010, p.218). This lack of information hindered the transfer of this input to Dell because of the added translation step. As a result, many contributions were ignored in favor of those that were easier to understand but not necessarily of higher quality. This example shows how more information needs to be transferred for the solution to be considered valuable, but other studies have come to similar conclusions (e.g., Beretta, 2019).

More broadly, the responsibility of connecting the distant perspectives—thus, successfully transferring information—rests both with solvers and seekers. This is particularly important considering that solvers can reformulate the problem. Solvers need to correctly recognize that they can solve the problem transferred by the seeker (Alexy et al., 2012). If not, they may miss important context and reformulate the problem in ways that lead to less useful or inapplicable solutions (Acar, 2019). In turn, seekers need to correctly identify which solutions are useful to them when they are transferred from the solvers (Piezunka and Dahlander, 2015)—a (more) difficult task if the purpose of the solvers' reformation is lost. If not, this can lead to the value of the solution being inaccurately assessed and deemed to be irrelevant or a poor fit (Alexy et al., 2012; Blohm et al., 2013; Huang et al., 2014).

4.2.4 Both the Seeker *and* the Solver Formulate: The Formulation Bridge

Despite the shared responsibility between seekers and solvers, problem formulation is still considered one-sided. The crowdsourcing literature—by and large—assumes that the seeker formulates a well-defined problem; the solvers merely solve it. In this view, seekers need to formulate the challenge problem carefully because no further iterations will be possible after it is thrown over the proverbial fence (Sieg et al., 2010; Wallin et al., 2018). However, this is not supported by related problem-solving literature, which views the nature of formulating and solving as iterative (Gralla et al., 2016) and inextricable from each other (Topcu and Mesmer, 2018). Through this lens, solvers (re)formulate in order to—usefully—apply their local knowledge to create their solutions, as elaborated above. Without this clarification, crowdsourcing's current view might drive seekers to formulate the problem more narrowly than needed to avoid apparent misunderstandings by solvers. We address this disconnect below.

In our view of this process, both sides play an important role in formulating (and solving). First, the seeker (gathers and) communicates the important aspects of their problem from their perspective (Volkema, 1995, 1983). Then, they broadcast their (preliminary) formulation widely, handing it off to potential solvers. However, while the seeker's formulation ends, the process *continues* with the solvers. After the hand-off, the solver places the problem statement within their own range of experiences. Like

Peter in the Astronaut Glove Challenge, they develop a mental image of the problem and decide what the problem means to them: identifying or clarifying the need within their context, deciding where to (begin their) search for knowledge, and bounding what will be (un)acceptable (Baer et al., 2013; Nutt, 1993; Gralla et al., 2016). Solvers then proceed with their own solving process. Finally, after the second hand-off, the seeker may need to (re)interpret the solution to infuse the solvers' solutions.

Since both seeker and solver(s) are formulating (and solving), deciding where to hand-off from the seeker to the solver is crucial. This decision determines solvers' freedom and the effort needed to interpret and solve the problem. To help illustrate this, we introduce the formulation bridge construct. It depicts the seeker and solver(s) meeting somewhere along the spectrum of an ill- to well-formulated problem. At this meeting, the solver receives the hand-off from the seeker. The closer the hand-off is to the ill-formulated side of the bridge, the more leeway the solver has to formulate (and solve). The opposite is true if it occurs closer to the opposite side: the seeker retains more control over the formulation, allowing less (re)interpretation of their problem by solvers. Additionally, the domain of the formulation is another important dimension on this bridge. Here, both the seeker and the solver can decide what domain to formulate the problem in—figuratively picking a lane on the bridge. Once the solver is satisfied with their progress and performance, they hand the solution back to the seeker. The seeker then infuses the solution back into their domain, which can require a significant effort on the seeker's part if it was not already in their lane.

Figure 4.1 below illustrates one potential scenario. We show the individuals in grays, the constructs in black, and the hand-offs as "x"s. Here, the seeker—in dark grey—formulated the problem locally and left it relatively open-ended. After the hand-off, the solver—in light gray—decided to reformulate the problem according to their domain. After the second hand-off, the seeker then interpreted the solution across the domain lanes. Finally, they also assessed the solver's solution for its usefulness.

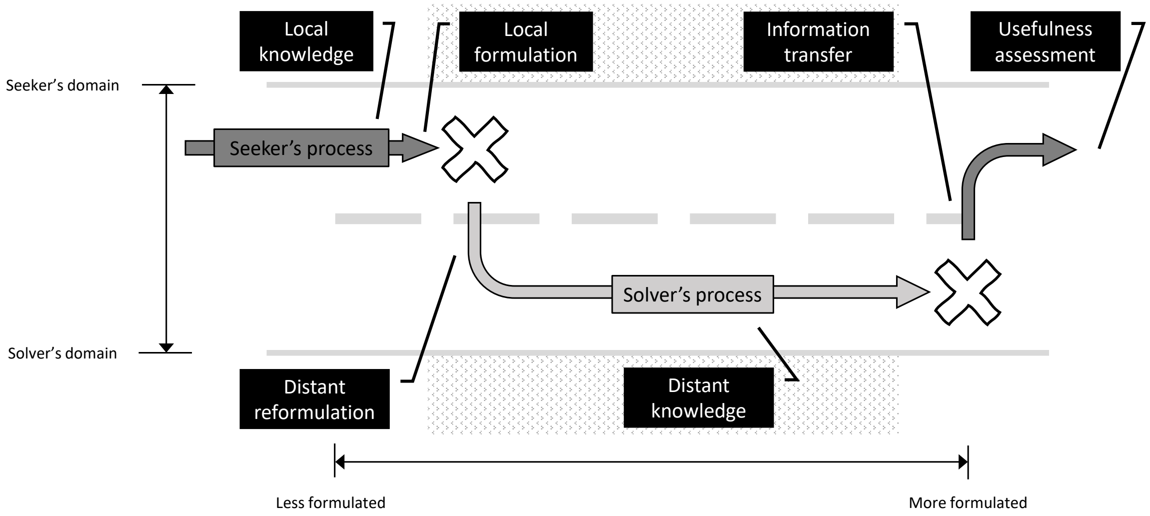

Figure 4.1: Formulation Bridge Conceptualization

Framed like this, the central question governing the broadcast mechanism is: where *should* the hand-off to the solver take place? Specifically, how much of the problem should each side formulate and solve, respectively? If seekers do it all, they are likely to constrain solutions to follow their local solving patterns, progressing far to the right within their lane (e.g., Afuah and Tucci, 2012). This increases usefulness to the seeker but limits the potential for novel insights. If left to solvers, the resulting open-ended problem formulation will likely receive a much wider variety of solutions, no matter its lane (e.g., Alexy et al., 2012; Poetz and Schreier, 2012). This increases the distant knowledge received from solvers. At the same time, these may be harder for the seeker to value, or altogether inapplicable to the seeker's problem. Additionally, the hand-off's location also impacts how the problem is described and communicated—affecting who self-selects to participate and how they solve (Ehls et al., 2020; Lifshitz-Assaf et al., 2022).

This paper explored the formulation bridge concept by examining how solvers traversed the bridge. In our empirical case study, we observed the hand-off of an open-ended problem to the solvers, their interpretation and (sometimes) reformulation of it, the knowledge they harnessed to solve it, and how they handed the solutions back to the seeker. These allowed us to understand the contours of solvers' problem (re)formulation, which in turn informed how formulation across the bridge could work best.

4.3 Research Setting, Data, Methods

We conducted an in-depth case study of a citizen's forum event within NASA's Asteroid Initiative program to explore the formulation bridge construct. Below, we describe the relevant background on our research setting and an explanation of our research design.

4.3.1 Research Setting: NASA's Asteroid Initiative Citizen's Forum

We picked a setting where we could observe the dynamics of the formulation bridge: one where an organization engaged with external, distant experts on a complex problem and gave them the leeway to reformulate. NASA's Asteroid Initiative Citizen's Forum fit these criteria: the agency sought citizen input on a highly technical, programmatic decision on an upcoming planetary defense spacecraft (Tomblin et al., 2017). NASA partnered with the Expert and Citizen Assessment of Science and Technology (ECAST) network to organize, coordinate, and execute two identical forums in two US cities—Boston and Phoenix—in late 2014 (Tomblin et al., 2015). Each event convened approximately 90 volunteers who sat in groups of six to eight for a full day. No volunteer had prior involvement in the aerospace industry. Organizers provided visual and written briefing materials that conveyed NASA's formulation of the problem in an accurate yet accessible way. Organizers also encouraged participants to deliberate their perspectives on the problem at their table before providing their input.

This event served our research purposes in several ways. First, NASA explicitly engaged with domain outsiders. The organizers recruited participants for their distance: anyone with previous NASA or space industry involvement was excluded. This yielded a population of participants that brought a wide range of other experiences. Second, the event's focus group format prompted participants to voice their perspectives and rationales while solving—making a normally hidden thought process explicit (Cyr, 2015; Kitzinger, 1995). Here, we observed and captured their formulation and solving process, providing a unique insight into how they saw the problem and what they used to solve it. Finally, we engaged with NASA's Asteroid Initiative—the seeker—over several years. The initiative consisted of two programs. First, the Asteroid Redirect Mission (ARM), tasked with designing and testing a spacecraft bound for an asteroid. Second, the Asteroid Grand Challenge (AGC), tasked with engaging and forming collaborations with non-traditional entities to improve the agency's asteroid detection and mitigation capabilities—which was also the aim of the citizen's forum. This access allowed us to observe both how NASA formulated the downselect and how they interpreted and valued the input provided by the participants.

Before describing our research data, we provide a brief background on the problem participants faced. In late 2014, NASA faced a "downselect" between two viable mission options for its billion-dollar ARM. ARM would demonstrate deep space and planetary defense technologies to help protect the Earth against future asteroid strikes. It would travel to, retrieve, and place a large asteroid sample in lunar orbit. ARM's mission options—Option A and Option B, respectively—differed in how and what they retrieved. Per their descriptions, Option A would "get a whole asteroid:" visit an asteroid approximately 10 meters in size and retrieve it in full. In contrast, Option B would "pick up a boulder:" visit a much larger object and retrieve a two- to three-meter sample from its surface. See Table 4.1 for a summary. To NASA's ARM team, the decision between Option A and Option B required trading between several metrics at the same time: the complexity of the options, the uncertainty in target asteroids, their extensibility to future missions, and their acceptance by the space community. Recognizing biases within NASA, ARM's executives felt that external input would reach outside of their "echo chamber" and be a welcome factor when

NASA's leadership made the choice.

As part of the event's briefing, participants received this context in addition to the specifics about the problem: costs, technical risks, and how it informed future NASA missions. Accordingly, organizers informed participants that NASA was asking for their input to help select between two alternative mission options to design NASA's first planetary defense spacecraft. The aim was not for the participants to propose a particular technology. Instead, NASA was looking for input on *how* to make this decision, given the high technical, operational, and political uncertainty.

Table 4.1: Summary of Downselect Options presented to Forum Participants

	Downselect Options	
Attribute	*Option A*	*Option B*
Capture mechanism	'Bag' that will envelop the target	'Claw' that will pluck a sample
Size of asteroid visited (m)	7-10	>100
Sample size (m)	7-10	2-3
Unique challenge	Target characterization	Sample removal
Unique benefit	Sample volume	Relevance to future missions

4.3.2 Data Collection

We gathered data on both actors on the formulation bridge to support our analysis. For the seeker's dynamics, we observed their initial formulation and solving efforts, as well as the hand-off of solutions from solvers and their infusion. Specifically, how Asteroid Initiative personnel viewed and described the ARM downselect, and how they perceived the participants' responses and their influence on NASA's decision. For the solvers' dynamics, we observed the hand-off from the seeker to solvers and how they solved the problem. Specifically, how forum participants (re)interpreted NASA's downselect decision and structured their response. We explain these below.

On the seeker's side, we gathered data before and after the citizen's forum event. We conducted 58 semi-structured interviews with the relevant planetary defense personnel at NASA (Converse and Presser, 1986). They provided critical context on how NASA saw the mission's decision criteria before and after the engagement, why NASA chose to communicate certain information in the event's briefing material, and the value of the participants' input to NASA's decision between the options. Our interviews began over a year before the citizen's forum and continued for about a year after. Table 4.2 summarizes those interviews, spanning levels of management at NASA and their involvement with the Asteroid Initiative.

In addition to the interviews, we also collected the briefing material itself. These provided a formal statement of NASA's formulation of the problem as it captured what NASA deemed important for the decision between mission options. They allowed us to distinguish between the problem formulations and knowledge that NASA presented to the participants and those the participants brought in from their own experiences.

Table 4.2: Interviewees and their Roles in the Asteroid Initiative

Interviewee	**Asteroid Initiative Role**
Deputy Administrator, NASA	AGC initiator and executive sponsor
Deputy Associate Administrator, NASA	Interested observer
Director, NASA Advanced Exploration Systems	Senior management oversight
Planetary Defense Officer, NASA	Senior management oversight
Program Manager, NASA ARM spacecraft	Senior management oversight
Program Executive, NASA AGC	Program management
Program Executive, NASA Prizes and Challenges	Prizes and challenges support
Team Lead, NASA ARM independent review	AGC interested observer
Concept Lead, NASA ARM spacecraft	AGC interested observer
Robotic Systems Lead, NASA ARM spacecraft	AGC interested observer
CEO, Asteroid mining firm	Industrial partner
CEO, Asteroid non-profit organization	Science community partner

Notes: These interviews totaled 34.4 hours of recordings. The results of the citizens' forums were presented to the NASA personnel listed in this table.

On the solvers' side, we gathered data during the citizen's forum event. We focused on the verbal solutions to the broadcast problem. This is in line with other crowdsourcing activities, like idea generation, idea evaluation, or design tasks (see also Pollok et al., 2019b). Generally, these kinds of problems require less effort from solvers compared to crowdsourced design tasks or innovation contests (see Szajnfarber et al., 2020; Vrolijk et al., 2022). We randomly placed audio recorders on seven tables across the two forums. These recorded the participants' thought process, capturing how they perceived the problem and how they solved it.

In total, we recorded and transcribed close to 4.5 hours of deliberations across 46 individuals, or approximately 25% of all participants. We then extracted all utterances related to the choice between Options A and B. In these, we identified 438 solutions across the seven tables, removing any repeated solutions from the same individual. Though several participants at each table would sometimes agree, we did not note consistent groupthink among participants at the tables. Rather, participants at all tables freely and explicitly shared their own views. We also collected a total of 77 pages of observer notes[1], using them to verify our deliberation data.

4.3.3 Measures

We used the problem-solving constructs we described in our literature review to analyze the formulation process between seeker and solvers. Specifically, we coded our data for problem formulation, solution knowledge, information transfer, and usefulness. We operationalized the first two as follows.

Problem formulation: A problem's formulation describes the (mental) representation of the problem. In our data, we compared problems posed by NASA with problems introduced in the deliberation transcripts. Specifically, we coded whether each formulation in the deliberations was a restatement of those posed by NASA during the briefing or something identified and framed by the participant. Taking the organization's perspective, a problem was coded as *local* when it originated from NASA and *distant* when the participant introduced it.

Knowledge: Knowledge describes the information an individual draws on in their solution. As above, we compared the solutions provided by the participants to the content presented in the NASA briefing materials. If these overlapped, it

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[1] The first author served as one of the table observers at one citizen's forum event.

was coded as *local* knowledge: it originated from NASA and is not derived from the participants' knowledge bases. If it did not overlap, it was coded as *distant* knowledge. We recognize that there may be an overlap between knowledge presented in the briefing material and knowledge possessed by the participants in advance of the workshop—meaning they came to this knowledge without NASA's input. However, since participants were selected for their lack of prior exposure to anything space-related, we assume any overlap to be small.

Additionally, we were interested in the impacts of different formulation and knowledge choices. Specifically, how the participants communicated their solution and whether NASA perceived it as useful. Since these assessments involve substantially more subjectivity than the first two, we contracted independent workers via Amazon Mechanical Turk (MTurk) platform to code our data (see also Xiao et al., 2018; Zhang and Chen, 2019).

Information transfer: This describes the depth of information transferred in communicating the solution. We adapted Mayer's information transfer taxonomy to our context (Mayer, 2002). MTurk workers assessed whether an utterance contained any (or all) of the following: a *choice*, defined as an explicit preference between the two options; a *comparison*, defined as explicitly contrasting the two options to themselves or another reference; or an *explanation*, defined as an explicit statement of the basis for the choice or comparison. Per Mayer (2002), a statement that includes an explanation conveys more depth than one that does not. Therefore, in our analysis, workers coded utterances that included an explanation as *high depth* and any others as *low depth*.

Useful: NASA defined what useful meant in this context. In our interviews, NASA personnel stated that input from the citizen's forum changed their view and assessment of the ARM downselect—a useful outcome for this exercise. This input included the participants' perceived risks and benefits for options A and B. It also included their broader sentiments: i.e., what they liked or did not like about the two options, or how they thought the general public would react to each option. Note that these formulations of the ARM downselect are broader than those presented in the briefing material—NASA personnel only realized their utility to the decision once they began reviewing the solutions. Therefore, we could not perform a direct comparison of as we did with knowledge and formulation. Instead, we used our interviewees' description of *useful* input[2] by the participants to code our data. Here, we contracted MTurk workers to assess whether each utterance included the description of a risk, a benefit, or a sentiment as defined above.

In all, 66 unique MTurk workers coded a median of 12 solutions each. We mitigated the inherent variability of these workers in two ways. First, only MTurk "master workers" coded the data: those who, per the platform, have demonstrated a high degree of success across various coding tasks. Second, we set a high threshold of agreement among coders per solution. Seven workers coded each solution for both variables of interest, and we required that least six out of seven agreed (>86%) to assign a code. We ran our analysis for a lower level of agreement—five out of seven master workers—and reported where the results were robust to these differences. We provide more information on this coding process in Appendix A.

4.3.4 Controls

Our analysis also included four control variables: gender, solution length, location in the discussion, and table effects. We included these to rule out alternative explanations for the observed combinations of knowledge and formulation on the perceived usefulness

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[2] NASA's Asteroid Initiative personnel did not code the utterances in our data. However, their rich descriptions of what changed their thinking about the downselect and the crowd's input allowed us to create the rubric to code this ourselves.

of the result. First, we controlled for gender. We included a dummy variable for each participant to account for a lower likelihood of women participating in decision-making and group discussions (Caspi et al., 2008; Denton and Zeytinoglu, 1993; Hyde and Deal, 2003; Rocca, 2010). Second, we controlled for content. We included a variable for the number of characters in each solution, as the number of words in the utterance might be (wrongly) equated with depth of information. Third, we controlled for the time when the participant uttered their solution. We speculated that useful solutions would appear throughout their deliberations, not just towards the end (Cyr, 2015). A focus on solutions at the end of the deliberation, like those in solvers' written surveys, would ignore those provided earlier. To corroborate this, we included a variable that captured when the solution was verbalized. Lastly, we controlled for differences across tables. We are interested in individual contributions within the deliberations, not the effects of their group on these outcomes. As such, we included variables for each table tp ruled out any table-specific dynamics.

4.4 Findings

Below, we explored the formulation bridge concept through our empirical study. First, we examined the prevalence of, and relationships between, the key constructs through a quantitative analysis. Then, we used our qualitative data to interpret the quantitative findings.

4.4.1 Quantitative Results

First, we examined the extent of problem reformulation during the citizen's forum. This meant examining whether participants introduced different perspectives on the ARM downselect than articulated by NASA. In other words, did the solvers switch lanes on the bridge? If our data did not include these, the formulation bridge concept would lack an important supporting pillar.

We found that participants reformulated the problem often: that is, they introduced (and solved) a different problem than what NASA asked them to address. We tabulated the solutions according to the knowledge and problem formulation variables, and whether they were coded as distant (introduced by the participants) or local (provided by NASA)—see Table 4.3. Two-thirds of solutions addressed distant problems that were formulated by the participants instead of addressing NASA's formulation of the problem. Additionally, about half of all solutions were formulated and solved locally.

Table 4.3: Summary of Solutions by Knowledge and Formulation

		Problem formulation					
		Local (to NASA)			*Distant (to NASA)*		
		Solutions	Useful	High depth	Solutions	Useful	High depth
Knowledge	*Local*	55	0.4	0.38	67	0.58	0.57
	Distant	99	0.57	0.42	217	0.56	0.63

Notes: n = 438 solutions, sorted by the formulation and knowledge codes. For each combination, we list the fraction of usefulness and high depth of information.

Next, we examined how choices on the bridge impacted the solution outcomes. Specifically, we used a logistic regression to examine the relationships between the participants' problem-solving process, the depth of the information transfer, and the usefulness of the solution.

We found a mediated relationship between these constructs. Solutions addressing a distant formulation and drawing on distant knowledge were consistently less likely to be deemed useful by the seeker. However, problem reformulation by the participants was a significant factor in the depth of information provided in their solutions. In turn, this depth was a significant factor in the usefulness of the solutions. We explain this relationship below.

Table 4.4 presents the descriptive statistics and correlation matrix for our variables and controls. Since the variables for information transfer and usefulness have a relatively high correlation, we made sure that this would not be a problem for our analysis. We checked for multicollinearity with respect to usefulness by calculating the variance inflation factors (VIF) for all variables. The highest value was, as expected, the interaction of local knowledge and local formulation at 5.5. All other VIF values were below 3.5—depth was 1.2—which is below the conventional VIF cut-off of 10 (Hair et al., 2006).

Table 4.6 presents our analysis of the relationship between the problem-solving process, depth of information transfer, and usefulness. We are interested in the effects of the solving process on the solution's usefulness, and how solutions are communicated may play a role in this process. As such, we ran three models: Model 1, where the dependent variable is the depth of information in the solution; Model 2, where the dependent variable is the usefulness of the solution; and Model 3, where we add depth of information transfer as an independent variable to Model 2. We included the control variables in all models.

Model 1 showed the effects of the problem-solving process on the depth of information presented in the solution. Here, problem reformulation by participants was positively related to information transfer: the effect of a distant problem on depth is positive (Model 1: 0.88, $p = 0.039$). This implies that when participants reformulated the problem, their solutions were more likely to include an explanation of their solution. The effect was robust to different levels of agreement among MTurk workers.

Models 2 and 3 show three effects of the problem-solving process on the solution's usefulness. The first connected distant formulations, the the solution's usefulness, and the depth of information transfer. Solutions to distant formulations were (weakly) positively related to usefulness (Model 2: 0.72, $p = 0.086$), but this effect was no longer significant when the depth of information transfer was included (Model 3: 0.55, n.s.). Additionally, depth of information transfer was positively related to usefulness (Model 3: 1.34, $p = 0.000$). Combined with the results in Model 1, these implied a mediated relationship (Baron and Kenny, 1986): problem reformulation by the participants increased usefulness *when* they included an explanation of their reasoning.

Table 4.4: Descriptive Statistics: Means, Standard Deviations, and Correlations

Variables	**Mean (SD)**	**1**	**2**	**3**	**4**	**5**	**6**
1. Usefulness (Yes or No)	0.55 (0.50)						
2. Depth (High or Low)	0.54 (0.50)	0.40***					
3. Distant knowledge	0.72 (0.45)	0.06	0.07				
4. Distant formulation	0.65 (0.48)	0.06	0.20***	0.13***			
5. Solution length	146.84 (114.73)	0.39***	0.39***	0.06	0.03		
6. Position in discussion	0.51 (0.29)	0.05	-0.06	-0.11**	-0.06	-0.02	
7. Gender	0.55 (0.50)	0.08	0.09*	-0.05	-0.02	0.03	0.10**
8. Table 1	0.15 (0.36)	0.04	0.04	-0.04	0.14***	0	-0.01
9. Table 2	0.12 (0.32)	0.06	-0.05	0.04	-0.03	0.04	-0.04
10. Table 3	0.16 (0.36)	-0.13***	-0.18***	-0.05	-0.15***	-0.10**	0.02
11. Table 4	0.10 (0.30)	-0.03	-0.01	-0.03	-0.07	-0.05	-0.03
12. Table 5	0.15 (0.36)	0.06	-0.02	0.03	0.09*	-0.11**	0.08*
13. Table 6	0.12 (0.32)	0.01	0.05	-0.02	-0.03	0.12**	-0.02
14. Table 7	0.21 (0.41)	0	0.15**	0.07	0.04	0.10**	-0.02
Variables (con't)	**7**	**8**	**9**	**10**	**11**	**12**	**13**
8. Table 1	-0.12**						
9. Table 2	-0.04	-0.15***					
10. Table 3	-0.02	-0.18***	-0.16***				
11. Table 4	-0.05	-0.14***	-0.12**	-0.14***			

12. Table 5	0.15***	-0.18***	-0.15***	-0.18***	-0.14***		
13. Table 6	-0.01	-0.15***	-0.13***	-0.16***	-0.12**	-0.15***	
14. Table 7	0.08	-0.22***	-0.19***	-0.22***	-0.17***	-0.21***	-0.19***

Notes: * $p < 0.1$, **$p < 0.05$, *** $p < 0.01$ (two-tailed tests).

Table 4.6: Results of the Mediator Analysis Using Logistic Regressions

	Dependent variables					
	Model 1: Depth of information		*Model 2: Usefulness of solution*		*Model 3: Usefulness of solution*	
Independent variables	Est.	RSE	Est.	RSE	Est.	RSE
Distant knowledge	0.17	0.41	0.71*	0.38	0.76*	0.39
Distant formulation	0.88**	0.43	0.72*	0.4	0.55	0.42
Distant knowledge x Distant formulation	0	0.52	-0.83*	0.5	-0.96*	0.52
Depth of information					1.34***	0.25
Controls						
Gender	0.46**	0.23	0.34	0.23	0.23	0.24
Solution length	0.01***	0	0.01***	0	0.01***	0
Position in discussion	-0.32	0.38	0.55	0.38	0.68*	0.4
Table 2	-0.58	0.42	0.07	0.42	0.28	0.46
Table 3	-0.83	0.4	-0.75*	0.39	-0.58	0.4
Table 4	-0.03	0.44	-0.31	0.45	-0.36	0.46
Table 5	-0.16	0.37	0.22	0.39	0.3	0.41
Table 6	-0.11	0.41	0.48	0.42	-0.52	0.44
Table 7	0.44	0.37	-0.37	0.39	-0.55	0.4

Notes: $n = 438$ solutions for all models. Model 1 predicts depth of information, while Models 2 and 3 predict usefulness of solutions.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ (two-tailed tests); R-squared values for Models 1 through 3: 0.245, 0.202, 0.267.

We tested this indirect effect using bootstrapping procedures (Hayes and Preacher, 2014; Imai et al., 2010). The estimated indirect effects across 1000 simulations were statistically significant and greater than zero (average casual effect: 0.048, p = 0.006), supporting our regression analysis. This indirect effect was robust to different levels of agreement among MTurk workers.

The second effect connected distant knowledge to the usefulness of the solutions. Specifically, distant knowledge was positively related to the usefulness of the solution (Model 2: 0.71, p = 0.068), regardless of the depth of information transfer (Model 3: 0.76, p = 0.064). This implied that when participants included local knowledge in their solutions, they were more likely to be useful—consistent with the crowdsourcing literature. The effect was robust to different levels of agreement among MTurk workers.

The third effect connected distant formulation, distant knowledge, and usefulness of the solutions. Here, the interaction of distant formulation and distant knowledge was negatively related to the usefulness of the solution (Model 2: -0.83, p = 0.095), even taking information transfer into account (Model 3: -0.96, p = 0.069). This implied that redefining the problem and solving it with their knowledge is less likely to be considered useful. However, we discarded this result since it was *not* robust to different levels of agreement among MTurk workers.

4.4.2 Qualitative Interpretation

We then took a closer look at our deliberation data to better understand our results. The representative examples below deepened our understanding of the dynamics generating the quantitative results above.

4.4.2.1 Problem reformulation and usefulness

We observed participants using their personal or professional perspectives to reformulate NASA's problem. Sometimes, this meant imposing their non-space perspectives onto the context; other times, this meant taking the problem out of the space context and mapping it to a different one. These always resulted in a different problem than articulated by NASA in the briefing materials. We present examples of both types below.

When participants imposed their perspectives on the problem, they articulated their existing views within the context and used these to solve the problem. Often, participants would articulate their existing tolerance for risks and benefits and map this to the ARM downselect. For example, Pete[3] described his hesitancy towards technical risk in terms of the risks associated with controlling each option's spacecraft. In this framing, he justifies his concerns by comparing Option B's proposed landing to the difficulties that a European spacecraft—Rosetta—faced attempting to perform a similar maneuver. Note that the difficulty of controlling each spacecraft was not a formulation of the problem presented to participants. Likewise, the Rosetta mission was not part of NASA's briefing material.

> Pete: "[Option B is] more technically difficult. Knowing that what happened the other day where [Rosetta] bounced and landed [on a comet] in different spots. How much control do you have on an object that is moving fast and chaotically? [For Option B] to land over a specific boulder and pick it up, that to me sounds extremely difficult."

By mapping the problem to a different context, participants could evaluate its specifics and their choices in a more familiar light. For example, participants reformulated the ARM downselect into the real estate context. Below, the facilitator prompted her table on (one part of) NASA's formulation of the problem: the public's excitement around planetary defense. Instead, the table's participants took this question in a different direction. Though Liz, Kristin, and Bernard thought it was, they also emphasized that excitement is a poor decision criterion and should be outweighed by more practical concerns. They used their real estate example to make that point in a more familiar way.

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[3] All names used in this article are pseudonyms.

> Facilitator: “So [a] planetary defense [mission] is sort of exciting, you mean?”
> . . .
> Liz: “It’s exciting like you said, but the majority of America thinks—”
> [crosstalk]
> Bernard: “I’m not going to say, ‘I’m going to spend a bunch of money because I’m doing something exciting.’”
> Kristin: “Like, are you going to buy a house because it has a nice color? Or are you going to buy a house because it’s stable and—”
> Bernard: “Exactly, and the school system is good.”

Per our results, the participants’ elaboration when reformulating made these solutions more likely to be recognized as useful. The group setting encouraged participants to verbalize their interpretation of the problem and their solving approach, no matter how they decided to solve it. Still, participants explained more of their thinking when they chose to solve a reformulated problem instead of NASA’s formulation. As the above examples show, they communicated how their preferences mapped to the context, why they thought their formulation of the problem was important, and how their experiences with similar scenarios compare to the associated risks, benefits, and perceptions of the options. This fuller description allowed reviewers, and NASA, to better assess the usefulness of their response. If, instead, they omitted the basis of their solution, NASA might not understand its relevance and would likely deem it not useful.

4.4.2.2 Distant knowledge and usefulness

Participants also solved the ARM downselect as formulated by NASA, addressing the problem as given to them in the briefing material. In these cases, the participants did not take the problem into their domain’s lane as described in our bridge diagram. Instead, participants continued to solve the problem within the context and the formulation provided. Per our results, they were more likely to contribute useful solutions when using their own knowledge to solve it. Additionally, distant knowledge was not impacted by the depth of information transfer—likely because the solutions addressed the seeker’s original understanding of the problem. For example, introducing different ways of deciding between ARM's downselect options. One part of NASA's formulation asked what the important criteria were in choosing between the two mission options. Here, some participants drew on their background and introduced criteria that had not been a part of the briefing materials instead of selecting one that had. Below, Gabby introduces "more bang for our buck" as her most important criterion. She then picks the option that, in her view, provides the most benefits for future missions to Mars (according to NASA) for its cost. Where NASA typically assesses benefit in terms of mission requirements, Gabby's solution values future NASA needs as well. It is a criterion that is not typically considered in choosing a spacecraft architecture but is critical to her support for the mission—and potentially the wider public's support as well.

> Gabby: "I feel like [Option] B is actually more bang for our buck, right? In the sense that you're still going to come back with a hunk of something to study, and in the process, you will be learning or attempting to learn and devise a way of doing things that will help us, you know, get to Mars."

4.5 Discussion and Implications

Organizations perform well when they effectively solve problems (Nickerson and Zenger, 2004; Nonaka, 1994), and there is a growing recognition that distant solvers can help (de Jong, 2016; Jeppesen and Lakhani, 2010; Poetz and Schreier, 2012; von Hippel, 2017). Both scholars and practitioners have explored how that can best be accomplished: scholars have studied the interaction(s) between seeker and solvers (Lifshitz-Assaf, 2018; Piezunka and Dahlander, 2015; Liu et al., 2021), practitioners have experimented with different ways of engaging with these individuals (Gustetic et al., 2018; Shergadwala et al., 2020). Our work contributes to their efforts, both theoretically and practically.

4.5.1 Theoretical Implications

Our aim with this work was twofold: to better understand the broadcast mechanism and make progress towards reliably good outcomes when used. To this end, we introduced the formulation bridge concept. It conceptualized the interaction between seekers and solvers in a new way, thereby developing theory about the shared problem-solving processes. First, it gave us a structure to clarify the roles between the two. Specifically, problem formulation is not a one-sided (set of) decision(s) at the start of the OI process (e.g., Paik et al., 2020; Afuah and Tucci, 2012). It is also not solely a self-motivated activity individuals draw on for their own (consumer) innovations, unconnected to other aims (e.g., von Hippel, 2017; Hienerth, 2006). Instead, the bridge represented a space where the seeker's efforts are met, and continued, by the solvers across domain boundaries. It also highlighted how both seeker and solver(s) bear responsibility for formulating how the seeker's problem would be solved.

Second, the bridge concept—specifically, the bridge's span and width—also gave us a structure to describe the interface between the seeker's and solvers' formulation. Its span highlighted the importance of *when* the hand-off occurs in the formulating and solving process. This translates to *where* in our bridge concept: does the seeker hand the problem off on the more-formulated side of the bridge, where little room remains for the solvers to reformulate into different domains? Or, like with NASA's ARM downselect, do they hand off closer to the less-formulated side, where solvers have the leeway to do this productively? Its width highlighted how solvers choose *what domain* they reformulate into. Much like selecting the knowledge they use to solve it (e.g., Acar and van den Ende, 2016), solvers also face the choice to stay in the lane designated by the seeker or move into their own.

In our setting, we showed that an early hand-off may result in useful solutions, provided solvers communicate their solutions adequately. Throughout their formulation and solving process, solvers were guided by their perspectives. They (re)formulated the problem as they saw fit—be it in the seeker's lane or their own—and solved it with the knowledge they thought was most appropriate. Both ways of traversing the bridge resulted in useful solutions. However, solutions to reformulated problems required more detailed descriptions to be recognized as useful.

These findings emphasize two important aspects of the broadcast mechanism: the value of an early hand-off and the importance of information transfer. First, an early hand-off can broaden the organization's view of the problem. The broadcast mechanism usually attracts solvers from a wide variety of domains (Jeppesen and Lakhani, 2010; Szajnfarber et al., 2020). Here, a less-formulated problem could prompt solvers to draw on their perspectives to reformulate the seeker's problem to continue their solving. In doing so, their various problem formulations may provide the seeker with a (more) extensive problem landscape than the seeker's organization could—potentially, revealing different—or overlooked—aspects of it. At the same time, the set of formulations returned to the seeker would mitigate the risk of defining the problem in a sub-optimal way (e.g., Dane, 2010; Bilalić et al., 2008).

Second, information transfer plays a significant role in correctly assessing solutions to reformulated problems. Scholars have called attention to the importance—and difficulty—of recognizing and absorbing distant solutions (Piezunka and Dahlander, 2015; Pollok et al., 2019b; Zobel, 2017). Reformulation by the solvers increases this difficulty, as it introduces a mismatch between the seeker's problem and the one that is solved. In our setting, solutions that did not address NASA's prompts lacked the common reference point provided by the briefing materials. When this happens, the resulting solutions might look quite different from what the seeker is expecting—and thus, are harder to recognize. Our findings clarify that the depth of the information transfer is a crucial factor in (recognizing and) determining their usefulness (see also di Gangi et al., 2010).

4.5.2 Practical Implications

Our work also guides practitioners looking to distant solvers for input. First, they should plan for rich interactions with such individuals. Distant and useful solutions are at higher risk of being ignored due to their differences with the organization's knowledge base. Here, the (added) effort required to understand the solvers' perspectives and interpret the solutions is part and parcel of a successful engagement with them. In our setting, participants communicated the needed depth verbally—they were encouraged to explain their perspectives to their groups. Here, the long-form responses captured most of the useful solutions. Other methods of facilitating this exchange could also accomplish the appropriate levels of information transfer.

Second, solvers' formulations of the problem *themselves* may open productive solution paths for the seeker. In crowdsourcing, we broadcast a problem in the hopes of finding better solutions by searching outside of organizational and domain boundaries. However, rigid formulation risks defining the problem too closely to a pre-determined solution or imposing unfeasible requirements. And as the Astronaut Glove Challenge demonstrated, better solutions can depend on different perspectives of the problem. With an open-ended problem, the various solvers can reformulate the seeker's problem in various ways, potentially spanning the tradespace of (new) avenues to pursue. Ultimately, the solvers' reformulations of the seeker's original problem could form the start of further exploration by the seeker (e.g., Hienerth, 2006)

4.6 Conclusion

This paper introduced and explored a theoretical concept to better understand how OI's broadcast mechanism worked. The formulation bridge concept highlighted how both the seeker and the solver(s) share the task of formulating the problem. It also highlighted how crucial this interaction is to get useful solutions. Our findings supported this view by unpacking links between the solvers' formulation and the usefulness of their solutions. These results lay the foundation for future work that elaborates how this exchange happens and when it makes sense to meet somewhere on the bridge.

Chapter 5—To Impose, To Incentivize, or To Subsume

How Solution and Solver Uncertainties Influence Problem Formulation Decisions in Crowdsourcing

5.1 Introduction

Technical organizations regularly face complex innovation problems which are crucial to their success. While the literature has proposed various approaches to tackle them, some innovation scholars have suggested opening them up to individuals outside of the problem's focal domain or industry (Chesbrough, 2003; von Hippel, 2005). Individuals in the *crowd* (Howe, 2006) have different knowledge and solve differently, meaning they can search for knowledge that is outside of the organization's reach (Afuah and Tucci, 2012; Jeppesen and Lakhani, 2010). Their input can help the organization overcome the limitations of expertise, like domain entrenchment, fixation, and other shortcomings (Dane, 2010; Purcell and Gero, 1996; Cañas et al., 2003). Crowdsourcing, and its related implementations like innovation contests, have resulted in input that broke new ground—even for complex problems (Szajnfarber et al., 2020; Murray et al., 2012; Suh and de Weck, 2018).

But delegating (parts of) a complex problem to outsiders is difficult. Complex problems are complex for a reason: they require expensive infrastructure, extensive cross-discipline training, or tacit domain knowledge to solve (Hobday, 1998; Nonaka, 1994; Maier and Rechtin, 2000). For problems in related domains, the solution-*seeker* may approximately know what kinds of designs interface with their existing systems; allowing problem-*solvers* to explore others will likely be unproductive. At the same time, many would-be solvers may not tackle the problem successfully: lacking the resources and knowledge that the seeker possesses, they may meet barriers that they—or their team—cannot overcome. So, the seeker must formulate this problem carefully: bounding the solvers' exploration to increase the chances of useful solutions while navigating the limits of their capability.

In this paper, we explore problem formulation for crowdsourcing. How does the seeker translate their need into a problem statement that outsiders—whose capabilities can be uncertain—can solve? Theory that describes problem formulation generally, and formulating for outsiders specifically, is sparse (Gralla et al., 2016; Wallin et al., 2018; Lopez-Vega et al., 2016). To help us understand this process, we turn to the systems engineering literature. Here, both scholars and practitioners have faced the issue of careful delegation in the design of engineered systems. These scholars have theorized two approaches to direct solvers to solve problems (Vermillion and Malak, 2020; Hazelrigg, 1998; Ryan and Wheatcraft, 2017): requirement allocation and objective allocation. We bring this theory into our analysis to connect our findings to existing literature.

We base our analysis on a multi-year fieldwork that captured multiple problem formulations. The lead author was embedded in NASA's CCP, an innovation contest office that opens up complex technical problems within the agency to the crowd. Through them, we gathered extensive qualitative data on these processes: months-long efforts that this office, and related SMEs, conducted to prepare important problems for outsider input. We summarized these data into vetted narratives of the process, which revealed 33 instances where the formulation team—the seeker—shaped solvers' solution spaces. We then inductively coded these instances to understand how the seeker decided on the rules for each problem statement.

The seeker used three actions to translate their need into a problem statement: *impose*, *incentivize*, and *subsume*. Each action shaped the solution space differently: *impose* defined acceptable or unacceptable designs; *incentivize* pushed solvers towards the seeker's preferences; *subsume* allowed solvers to explore as they saw fit. These appeared as progressively looser design rules in the problem statement to the solvers. Motivating the seeker's choice between the three actions was the seeker's knowledge of potential solutions and (estimates of) solvers' limitations. In short, the more the seeker knew what solutions would work, the stricter their decisions on the solvers' solutions space. However, *only* with the most knowledge of solutions could the seeker accommodate the solvers' limitations and allow them to explores solutions freely. Two of these actions mapped to the systems engineering approaches for problem formulation: *impose* and *incentivize* mirrored requirements and objective allocation, respectively. The third, *subsume*, presented a way for the seeker to absorb unwanted variability in the solvers' solutions.

Our findings shed light on an important part of the crowdsourcing process. They reveal dynamics that, until recently, have not been carefully studied (Wallin et al., 2018; Ehls et al., 2020; Sieg et al., 2010). Describing the hows and whys of the problem formulation process also provides practitioners with concrete tools to use in their own contexts. Additionally, connecting our findings to the systems engineering literature opens the door to further leveraging insights across these domains.

5.2 Literature review

5.2.1 Formulating the Problem for Others to Solve

Problem formulation is crucial in problem-solving (Mitroff and Featheringham, 1974; Newell and Simon, 1972). In this stage of the process, the seeker gathers the needed information to decide "what is part of the problem and what is not" (Volkema, 1995, p. 82)—naming and framing what will be addressed (Cross, 2004; Nutt, 1993). Here, they identify the need within their broader context, define (un)acceptable designs, and articulate a problem statement (Baer et al., 2013; Volkema, 1983). Thus, problem formulation translates an abstract need into a (more) concrete description that drives the ensuing problem-solving efforts and decisions (Gralla et al., 2016; Nutt, 1992).

Usually, formulation and solving happen cyclically. Problem formulation and problem-solving are separate but interdependent stages to reach a solution (Cyert and March, 1963). When the seeker solves the problem themselves, the problem's formulation guides them to search for knowledge to address it (Nutt, 1993; Louis and Sutton, 1991). Here, they search for (what they think is) useful knowledge, either inside or outside their existing knowledge areas or routines (Nelson and Winter, 1982; Katila and Ahuja, 2002). With a partial solution in hand, the seeker reenters the formulation stage and iterates until the solution satisfies the need to the best of their capabilities (Gralla et al., 2016; Winter, 2000). In practice, iterating between these two stages is a well-accepted part of arriving at a solution: normative models for the design process, for example, consistently feature iterative loops where the in-process formulation is refined based on new solution knowledge (Kossiakoff et al., 2011; Buede and Miller, 2016).

Problem formulation is even more important in the open innovation context. First, iterating between formulating and solving is no longer possible (Wallin et al., 2018; Sieg et al., 2010). Because of the nature of these activities, it would be untenable for the rules to undergo a significant change midway through a contest. As such, the problem statement is final, with little chance for course correction—the seeker throws the problem over a proverbial fence once it is formulated.

Second, the problem statement forms the common understanding between the seeker and solvers (Jeppesen and Lakhani, 2010; Pollok et al., 2019a). It describes what solvers will tackle and, by extension, what kinds of solutions the seeker expects (Vrolijk et al., 2022; Ehls et al., 2020). To create it, the seeker decides how to delegate the problem—either wholly or partially—and must clearly articulate the solver's role in their process. The specifics of the solving tasks—with its tacit knowledge requirements—could preclude certain potential solvers (Afuah and Tucci, 2012; Schweisfurth, 2017;

Szajnfarber and Vrolijk, 2018; Lifshitz-Assaf et al., 2022): an important consideration when the aim is to gather inputs from outsiders. Thus, problem formulation is one of the seeker's most important levers to influence the solving process.

5.2.2 The View from Systems Engineering

Delegating (parts of) a problem to others is also a core focus of designing complex engineered systems (Kossiakoff et al., 2011). As with all complex problems (Simon, 1957, 1972), a single designer cannot complete the design alone due to the limits of one's cognitive abilities (Grady, 2010). These designs span multiple domains, some requiring deep knowledge that can only be acquired through years of (cross) training (Maier and Rechtin, 2000). The designer—now seeker—must also receive input from other individuals. To do so, they decompose the design problem into smaller parts with defined interfaces, which they allocate to different actors—be they individuals or organizations (Baldwin and Clark, 2000; Eppinger and Browning, 2012). Thus, these complex problems will see teams with varying expertise working together. In this context, like in open innovation, the seeker must also formulate the design problem for others to solve: creating and overseeing a problem statement with the appropriate allocations. System engineering scholars recognize the importance of this step and its potential for inducing failures or costly rework (Boehm and Papaccio, 1988; Buede and Miller, 2016). Here, they have long studied how to best formulate complex designs: decomposing the design problem while ensuring each part of the design helps the whole address the need. Scholars have proposed two approaches to perform this formulation: requirement allocation and objective allocation.

5.2.2.1 The Requirement Allocation Approach

Under the requirement allocation approach, the seeker formulates the solving task as *meet this requirement*. Relying on their expertise, they define design aspects that are "unambiguous, testable, and measurable" (Ryan and Wheatcraft, 2017, p. 122). This decomposes the solvers' solution space into regions of acceptable and unacceptable designs, bounding what solvers can explore. The seeker then tries to craft clear statements reflecting these decisions, for example "the system shall weigh less than X kg" (Vermillion and Malak, 2020, p. 102). Normally, these are relatively easy to communicate (Buede and Miller, 2016; Hull et al., 2002; Bijan et al., 2013). The resulting problem statement emphasizes that the solvers have no leeway concerning these regions: they define how the solver's part of the problem helps address the seeker's overall need (Baldwin and Clark, 2000). If the solution is out of bounds, the solver's (partial) design will not interface with the other parts as the seeker has specified (Parnas, 1972; Ulrich, 1995; Eppinger and Browning, 2012), resulting in the whole falling short.

Many organizations have adopted or customized requirement allocation into their formal processes. Both professional communities and organizations have created reference materials for their members that use this approach as their backbone (Haskins et al., 2007; El Emam and Birk, 2000; Kapurch, 2010; Sommer, 2019). Regardless of the specific implementation of the approach, e.g., Quality Function Deployment, Spiral Models, or Agile Development (Mizuno and Akao, 1978; Maier and Rechtin, 2000; Kossiakoff et al., 2011), decisions made by the seeker bound subsequent solving steps.

However, the strict nature of this approach can present challenges. When using this approach, the seeker's decisions—by definition—limit the solver's exploration of designs. This presents two risks. First, the seeker can incorrectly declare a valuable region of the solution space to be unacceptable. These boundaries are created early in the design process, when the seeker is the least knowledgeable about how different designs will perform (Malak and Paredis, 2009; Aughenbaugh and Paredis, 2008). Thus, if the seeker makes these decisions when they lack the appropriate solution knowledge, they risk bounding solvers in a poor(er) region of the solution space, resulting in poor(er) designs from solvers (Topcu and Mesmer, 2018).

Second, the seeker can also prevent solvers from making tradeoffs that result in a better overall solution. The uncertainty of the seeker's solution knowledge means they do not fully understand the dynamics and tradeoffs among the parts of the problem. With strict bounds in place, solvers must adhere to the design that the seeker has described. Except for these boundaries, solvers cannot forecast how their design choices impact the whole (Baldwin and Clark, 2000). Thus, they might make design decisions that are ideal for their part of the problem but lead to poor(er) outcomes to address the seeker's need. These and other drawbacks—like specifying conflicting requirements (Salado and Nilchiani, 2016)—have prompted scholars to envision a different approach to formulate complex designs.

5.2.2.2 The Objective Allocation Approach

Under the objective allocation approach, the seeker formulates the solving task as *optimize this objective*. Here, they communicate the design objectives that give the solution its value (Collopy and Hollingsworth, 2011; Hazelrigg, 1998): specifying what they need the (whole) solution to achieve to be successful in the broadest sense (Abbas and Matheson, 2009). Unlike the above approach, where specificity is required, the objectives are open-ended statements like "the system should have minimal weight" (Vermillion and Malak, 2020, p. 102). This is a deliberate choice. No design is explicitly in or out of bounds. Instead, the approach encourages exploration across all design parameters to find the solution that best meets the stated objective.

Objective allocation converts the design problem into an optimization one: a common problem among many fields. Here, systems engineering scholars have leveraged insights and techniques from, e.g., expected utility theory (Hazelrigg, 1998; Topcu and Mesmer, 2018), game theory (Grogan and Valencia-Romero, 2019), and multidisciplinary design optimization (Martins and Lambe, 2013; Cramer et al., 1994).

Yet, despite its far-ranging theoretical roots, practical adoption of this approach lags (Topcu and Mesmer, 2018).

This approach is not without its challenges. With an eye towards their need, the seeker may easily derive an objective for the whole problem. But describing this objective in terms of each of the problem's parts is challenging. One begins the design process by decomposing the problem into defined parts, prescribing large swaths of the solution space through the system's interfaces—making design decisions this approach tries to avoid. These objective functions are also much harder for individuals to grasp (Collopy and Hollingsworth, 2011). Here, different techniques have been proposed that simplify a set of objectives to allocate them across the decomposed parts of the problem easily (see, e.g., Buede and Miller, 2016). Still, the challenge remains (Weigel and Hastings, 2004; Lee et al., 2014). Additionally, without boundaries on their designs, solvers might also make design choices in their part of the problem that negatively impacts the whole (Malak et al., 2015; Vermillion, 2016).

5.2.3 Connecting Systems Engineering to Crowdsourcing

Formulating a problem correctly is a common concern. Even Albert Einstein proclaimed that "the formulation of a problem is often more essential than its solution." (Einstein and Infeld, 1938, p. 92). Scholars increasingly recognize problem formulation's important role in open innovation; the resulting problem statement is "sine qua non" of this paradigm (Jeppesen and Lakhani, 2010, p. 1082). Yet, we still lack an understanding of this stage in the process (Wallin et al., 2018; Lifshitz-Assaf et al., 2022; Ehls et al., 2020).

The systems engineering domain has long recognized problem formulation as a concern as well. Wrongly formulating the problem could represent a massive setback for the seeker (Maier and Rechtin, 2000; Buede and Miller, 2016). To address it, scholars have conceptualized two normative approaches to this process, requirement allocation and objective allocation. These approaches have seen extensive scholarly work to understand how to best implement them to design complex engineered systems. Both approaches translate the seeker's need into a problem statement that delegates solving tasks to the solver. They aim to influence the solver's design choices when exploring the solution space. The approaches differ in how they accomplish that: how they declare undesirable regions of the solution space and how they communicate the interfaces between the solver's part of the problem and the whole.

Yet, it is an open question whether insights from systems engineering can apply to crowdsourcing. The iterative process of sensemaking, formulation, and solving is interrupted—an important difference between the two contexts. There is little (or no) room for change once the problem has been shared (cf. Gralla et al., 2016; Ehls et al., 2020). Instead, there is a greater risk of "errors of the third kind" (Mitroff and Featheringham, 1974, p. 383): the right solution to the wrong problem. While both systems engineering and crowdsourcing recognize the importance of problem formulation, we need to first understand *how* the seeker formulates for uncertain outsider input. If the seeker's actions align with these approaches, we could leverage system engineering insights in the crowdsourcing context. If not, we might broaden the conversation on formulating complex problems.

5.3 Research Setting, Data, and Methods

We conducted this work following approaches recommended in the literature. Considering the lack of theory described above, we pursued an inductive research approach: understand the phenomenon in its context to build theory that explains its dynamics (Edmondson and Mcmanus, 2007; Szajnfarber and Gralla, 2017). In our case, the phenomenon we were after would only be found in project documentation, interactions between individuals, and decision-makers' recounting of their decisions. Thus, we pursued a qualitative approach to gather and analyze our data (Babbie, 2015; Miles and Huberman, 1994). Below, we describe the setting we chose to pursue this question, what data we gathered, and how we analyzed it to arrive at our findings.

5.3.1 Research Setting

Our setting is CCP[1]. This program is NASA's flagship for complex innovation challenges. It finds topical technology problems across the agency where non-domain input and development activity and funding will be useful and launches an innovation contest to address them. The CCP works closely with the relevant NASA SMEs who run active projects in the relevant topic areas—they were the seekers in our context. These SMEs are (usually) intimately involved in formulating the problem: specifically, shaping it in ways that complement their internal work (Vrolijk et al., 2022). Contests' deliverables ranged from paper designs to small satellites to be deployed in orbit; their prize purses ranged from \$50K to \$5M. In these contests, the solvers usually form industry, academic, or non-affiliated teams to create their contest submissions—very rarely does the same team participate in multiple contests. As such, CCP challenges vary in topic, level of development, participants, and (NASA) stakeholders involved in the formulation of each contest.

We examined two multi-award, multi-year NASA challenges within this program: the 3DPH challenge and the CO_2 to Glucose challenge. The former challenged solvers to design and demonstrate additive construction technologies for Mars, which could 3D print the needed infrastructure on the planet's surface. This capability will massively reduce NASA's launch costs and the risks of radiation exposure to astronauts. The challenge launched in 2015 and ended in 2020. The latter challenged solvers to find and demonstrate an efficient pathway for converting CO_2 to glucose. Using this process as a basis, a NASA crew could manufacture many valuable materials during their long-duration stay on Mars. The challenge launched in 2018 and ended in 2021. Our fieldwork spanned both challenges.

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[1] The lead author was in the field between 2016 and 2020.

The two challenges provided us with multiple instances of the problem formulation process. Both the 3DPH Challenge and the CO_2 Challenge had multiple challenge stages where solvers had an opportunity to win a prize award. The seeker formulated a problem that solvers would compete for at each stage. While these focused on the same topic, they covered different aspects of the technology, asked for markedly different deliverables, or reevaluated previous rules. We captured five of these processes within our data.

This setting was ideal to address our gap. First, we captured multiple instances of the formulation process: these covered a range of topics, saw a spread of their prize purses, and were formulated by different SMEs, both inside and outside of NASA. Second, SMEs were deliberately formulating for non-NASA outsiders. Generally, SMEs want to reach outside the aerospace industry: several SMEs noted how they "fight constantly to get outside the known group of people and companies that we deal with." They recognize and use contests as a path to do so. Third, the contests and their outcomes mattered to the individuals formulating them. NASA ran active technology development projects on the same topics being challenged. The related SMEs were heavily involved in formulating these challenges because there was a chance that their outcomes could support their work. When asked how challenges fit into their ongoing work, one SME replied that they play "a very complementary role to what we're doing." SMEs would draw on their expertise to translate their need into the problem statement, focusing solvers' search efforts to play this complementary role. This way, they thought they could improve the chances of getting solutions that would work for their aims.

5.3.2 Data and Methods

In our context, formulating the problem meant translating an internal need into a contest's problem statement. In this process, SMEs decided on the problem's scope, scale, and deliverables. These would impact both who participated and what solutions SMEs received. In both challenges in our data, this translation happened across many months and many meetings. Additionally, various stakeholders, both inside and outside NASA, contributed to each contest's formulation process. Thus, capturing the relevant data for this analysis required a wide net.

To this end, our data consisted of interviews, project documents, and first-hand observations. First, we collected upwards of 65 hours of semi-structured interviews (Converse and Presser, 1986). These included interviews with all NASA and non-NASA formulation team members for both contests, as well as the CCP personnel who supported them during this process. While our questions about their context, work, and the contests were wide-ranging, we asked them to describe their discussions on the rules in detail—what they decided and why. To understand the effects of their decisions on the solvers, we also interviewed various teams across both contests.

Second, we collected upwards of 3500 pages of related documents. These included weekly minutes of formulation teams' meetings and those of the CCP, the contests' programmatic documents, multiple drafts of all rules and accompanying FAQ documents, and program documents of related NASA projects. Combined, these formed a contemporaneous picture of the formulation process and the context around it.

Lastly, we also conducted direct observations during several contest activities. We observed and took notes at contest formulation sessions, planning meetings, and the contests themselves. These gave us a first-hand account of the formulation process and the contest's dynamics.

We analyzed these data across several steps. First, to establish a record of problem formulation within the two contests, we created analytical chronologies (Langley, 1999; Miles and Huberman, 1994): detailed, vetted[2] narratives that captured what happened when and why. These triangulated the formulation processes across our

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[2] Key interviewees from our setting vetted these chronologies for accuracy.

various sources. We used these as a baseline to inform our subsequent analyses.

Next, we extracted instances of problem formulation decisions. We pored over the five formulation processes that the chronologies captured. Here, we identified instances where the formulation team deliberated and decided what should, or should not, be in the contest's problem statement, reflecting how SMEs created the problem statements. Each instance centered on one parameter of the problem, like "printed material strength" or "footprint of the conversion system." Our data produced 33 problem formulation decisions across the five problem statements.

Then, we performed two rounds of open coding (Strauss and Corbin, 1990). In the first, we explored *how* the SMEs formulated their problems. For each formulation decision, we returned to our data asking how SMEs translated their technical needs into the related rules in the problem statement. Here, codes like "we let solvers define the parameter" or "we set the parameter to a specific state" started to emerge. We grouped these codes into three categories, *impose*, *incentivize*, and *subsume*, each describing an action SMEs took to formulate. Examples of these actions appear in below

We then asked *why* SMEs decided to take these actions during the second round of open coding. The codes that emerged during this round suggested SMEs based their decisions on the kinds of solutions they thought would be successful. They also indicated that the depth of the relevant knowledge played a role: differences between knowing what a solution must do versus the details of what design(s) accomplished that were apparent. As such, we grouped these codes into three categories of *solution knowledge*: high, where the formulation team knew a solution's function and design; medium, where they only knew its function; and low, where they knew neither. Not all codes involved the SMEs' knowledge, however. In this round, codes like "the resource constraints are too high for challenge participants" also emerged. These suggested that the solvers' capabilities also influenced SMEs' actions. We grouped these under

Table 5.1: Coding of Formulation Actions

Formulation Action	Description	Coding Vignette	Sample Quotation
Impose	The seeker decides a design should be incorporated. Sometimes these matched the seeker's exact need (impose), sometimes these were tailored to the solvers (best fit)	Inflatable structures are a commonly used design and well-understood way of retaining pressure. However, SMEs did not want to (solely) rely on this technology to perform this function in their habitats. Instead, they wanted the printing systems and designs to incorporate this function into the printed structure. SMEs thus imposed rules against designs that included inflatables.	"We wanted pressure retaining structures that were constructed using 3D printing. So we really emphasized that in the rules to try to drive people away from using inflatables and try to maintain that consistently throughout the competition."
		SMEs wanted printing systems to demonstrate their ability to print adequately sized structures. However, they reconsidered imposing a full-sized design: it would be too expensive for solvers. Instead, SMEs chose a size that balanced the expected solvers' costs with the required functionality.	"We knew that full scale, I think that was about 100 square meters, was just going to be too big for anyone to design a printer that big and bring it to our location. It just wasn't going to happen. So we decided 1/3 scale was a reasonable size envelope for them to print."
Incentivize	The seeker drives solvers towards a function by awarding or removing points	With knowledge of what materials on Mars could be used for various feedstocks, SMEs incentivized certain (more common, less mission critical) options over others.	"And [the scoring rubric is] a sliding scale, and you get more points if you're spacelike [focused on Mars]. So that doesn't mean you can't do it, you just take the hit on materials if you want to use more Earthlike materials. And you can do that, but you get less points."

		Given the dangers of radiation and hazards of construction, SMEs wanted printing systems with very high levels of autonomy (ideally fully autonomous). But SMEs felt that requiring full autonomy would be too hard for solvers to comply with. Instead, SMEs would remove points anytime that a team had to intervene in their printing system's autonomous operation (a negative incentive).	"[On Mars,] you have to have autonomous systems, but that's very hard and very expensive. How do we do that. And different teams have different levels of autonomy. In the end we said, we can have autonomy, but it was too hard to do 100% autonomy, so we gave them an opportunity for manual interventions. But every time you did a manual intervention, you'd lose points."
Subsume	The seeker architects their system to address the parameter internally (or) at a later date. Any mention of design or function is omitted.	SMEs believed that requiring solvers to address, and test their systems to, the environmental conditions on Mars (specifically vacuum and temperature) would be too onerous for the solvers. So they left these criteria out of the rules.	"We typically [look at flammability, toxicity, and vacuum performance] when we look at new emerging materials for spaceflight. That's what NASA does. Like 'this looks good for this application, but this has no flight history. So, here are the things we have to do to evaluate it.' And sometimes, that informs [its redesign]: 'well it's flammable, can we add flame retardants to it? Can the material developer tweak the formulation somehow to meet our needs?' So it kind of starts that interchange in someway."
		While ensuring a sample's purity is an important part of the conversion process, SMEs believed that imposing these would be onerous on solvers and hard to implement. As such, no purity requirements were included. But SMEs knew that purifying their samples was a possibility.	"If I get 90% glucose and 10% of something else, say 2-, or 3-carbon compound which is actually toxic to the bacteria. Then that 90% glucose is no good to me. Unless I purify it, and I add another step. Because I would have to extract the impurity out, which is 10%. So there are going to be byproducts."

Table 5.3: Coding of Solution and Solver Knowledge

Knowledge	**Valence**	**Description**	**Coding Vignette**	**Sample Quotation**
Solver	High	The seeker knew solvers' capabilities would be limited here (e.g., money or expertise)	While SMEs wanted to test the feedstock materials in relevant environments, they realized that requiring vacuum tests would be too expensive for solvers.	"It's a fine line between attracting competitors and scaring them away. When you make it too hard— How many people have vacuum chambers. It just raises the bar, the level of entry. So we decided not to got as far as that. . . . We just didn't think the competitors could handle it."
			While SMEs knew that a conversion system's footprint (volume, mass, power) would be very important for a NASA application, they felt that including these requirements would be too difficult.	"[I]n doing the Centennial Challenge, you don't want to push it in such a way that it becomes impossible. That people say, 'I could have done it, but it became so impossible that I couldn't do it. I could have gone 50% of what they're asking for.' I don't want to eliminate that in the first step."
	Low	The seeker did not know or care about the limits of (potential) solvers' capabilities	SMEs want to print hollow habitats for NASA's astronauts and limit the amount of construction they would have to do while on the surface. In the 3DPH Challenge, they wanted printing systems to construct the required dome shapes without internal supporting structures. This is far outside what is common in 3D printing.	"If we had a competition and allowed support structures, we wouldn't be advancing the state of the technology. It would be the same as everyone would be doing today."

			SMEs want printing to be cost-effective and maximize using resources in-situ. In the 3DPH Challenge, they wanted printing feedstocks with a high ratio of in-situ material—greater than 70%, to be exact. They were unsure whether teams could accomplish this.	“It was an educated guess that materials fit for printing could’ve been made. . . . We figured that 70% indigenous material would make materials development challenging, and it would provide a significant cost savings for NASA—”
Solution	High	The seeker knew both function and design: exactly which solution(s) would meet the need	SMEs knew that biological-based systems might be able to accomplish the conversion but would not otherwise satisfy NASA’s needs for this system.	“And [a bio-based solution] wasn’t the system we were looking for. . . . The potential for physical chemical processes to be selective, to work quickly, to be controllable, is the main reason why we were interested in developing [the physiochemical conversion] approach.”
			SMEs drew on NASA’s previous work to set the crew’s volume and life-support criteria for all habitats.	“Designs must include a minimum of three 45 ft3 (1.3 m3) spaces allocated for Environmental Control and Life Support Systems (ECLSS) equipment.”
	Medium	The seeker did not know what design(s) would meet the criteria but knew the function they were targeting	SMEs knew that complete autonomy would be ideal for these printing robots. However, they estimated that teams could not accomplish this; it would be tough even for dedicated entities).	“It’s too hard for the teams to never have a manual intervention. In other words, we could have said ‘you need to have 100% autonomy,’ and the first time something goes wrong the team is out of the competition. But we didn’t want to knock teams out of the competition.”

		SMEs knew that they wanted to encourage material strength but did not have a specific target to achieve. They only put in a lower boundary to help articulate the problem.	“Also, the minimum load for compression cylinder was 1000 lbs is a very low bar; but we felt that we had to have a standard to qualify. We are going away from that and allowing the competition to push some of the quality. . . . As I said before, these are very low qualification levels.”
Low[a]	The seeker knew neither function nor design(s) that could address their need	The habitat’s architectural design determines what shape the printer would need to support. However, several SMEs were indifferent to its specifics when it was being formulated—wanting to focus on more important aspects.	“I don’t really care what [the habitat] looks like, but I want to make sure it doesn’t kill me.”

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[a] Only one instance of Low Knowledge appeared in our data.

the category *solver knowledge*. We provide examples of these codes in Table 5.3 below.

Finally, we used axial coding to connect the categories we created (Strauss and Corbin, 1990). Here, we established that the SMEs' uncertainties on successful solutions and the solvers' capabilities influenced how they translated each parameter into the problem statement. We expand on this process below.

5.4 Findings

During the 3DPH Challenge, NASA CCP summed up the SMEs' efforts as follows: "The rules team is strategically planning for a set of rules to push the technology to its limits while reducing barriers to entry for the competitors." This is a concise summary of the balancing act that happened every time a formulation team crafted the problem statement for the challenge. SMEs were looking for solutions that could meet the technical challenges they faced. Yet, they were conscious of the capability uncertainties of the (supposed) solvers. Thus, SMEs needed to craft a version of that problem that was useful to them yet solvable through the challenge(s). We found three actions that SMEs took to craft the problem: *impose*, *incentivize*, and *subsume*. We describe these below and how deciding between them depended on the SMEs' knowledge of solutions and solvers' capabilities.

5.4.1 What Actions did SMEs take to Formulate the Contest's Problem?

SMEs took one of three actions to formulate their problems. They applied these actions to the most important parameters to translate their (at times nebulous) technology needs into a problem statement. The actions differed in how strict they held solvers to the specification of a parameter: the stricter the action, the more it would impact their solving, or the SMEs hoped. The strictness impacted the leeway given to solvers in their designs and the decisive tone of the rule that resulted from the action. I describe the three actions below.

5.4.1.1 Impose

The strictest action forced solvers to comply with the designs the SMEs specified. Across several parameters, SMEs *imposed* design values (like habitat surface area), design thresholds (like a minimum mass fraction for printer feedstock), or even design families (like powder bed printing methods) on the challenge problem. Decisions on these specifications were completely in SMEs' hands, forcing solvers to incorporate, or exclude, the stated design. Of the three actions, impose produced the strictest rules. If solvers did not follow the stated design, their solutions would be ineligible for points or disqualified. Solvers would have no choice if they wanted to succeed in the contest.

The language used to describe rules based on this action was as decisive as its rules were strict. Whether SMEs used this action to include or exclude designs, they communicated these with unambiguous statements. The problem statement would often use words like "shall," "must," or "are required" to describe the rule. Sometimes, the SMEs provided a detailed diagram of what they were expected to produce. For example, describing a surface area in a habitat allocated for life-support systems: "Designs must include a minimum of three 45 ft3 (1.3 m3) spaces allocated for Environmental Control and Life Support Systems (ECLSS) equipment." In addressing potential solvers, SMEs would talk about these rules with little room for interpretation and a clear warning to comply. In a frequently asked questions document in the 3DPH Challenge, SMEs reminded solvers of an imposed design threshold and that "failure to meet this minimum requirement will result in disqualification." These examples show that when SMEs took this action, they expected their decision on a particular parameter to be immovable.

5.4.1.2 Incentivize

Using a less strict action, *incentivize*, SMEs encouraged solvers to explore designs that addressed, or made progress toward, the intended functions. The nature of the challenge meant that "teams are going to go after the maximum points," one SME explained. To win, solvers would gear their solutions to earn the most points according to the metrics allocated by the SMEs. With the rewards on a gradient, SMEs communicated their preferences: if solvers wanted to win, their solutions needed to follow the indicated direction and outperform others according to the SMEs' parameter. The action highlighted the functions that solvers' systems should address and their preferred outcome(s).

While this action specified *what* they wanted the solutions to do, SMEs intended to "leave as much room as possible for innovation" on *how* solvers would do that. The design choices would be in the solvers' hands. For example, to encourage the use of resources available on the Martian surface, SMEs rewarded teams if a feedstock included certain materials over others. Similarly, SMEs rewarded teams for fewer interventions during printing to encourage autonomous operations. These rules enticed solvers to find (new-to-NASA) designs that addressed the function(s) in question. But at the same time, they left specific design choices—like the feedstock's exact recipe or the solution's autonomous system–up to the teams. In sum, the action translated the SMEs' preferences into the challenge, while at the same time communicating the need to explore various designs that might meet them.

The rules emphasized the related scoring gradient to communicate SMEs' preferences. The gradient described how the SMEs would reward solvers' solutions—a proxy for how well their designs addressed the intended function. The rules usually presented the gradient and its tiers in tables, noting that the tiers with the highest rewards "being the most preferred." The rules also described the gradient as larger rewards for minimizing or maximizing a particular parameter. Sometimes, the SMEs rewarded solutions directly in points: a better performance—being more successful at addressing the function—translated directly to more points. Other times, they rewarded the solutions through points multipliers, where their performance would significantly impact how other parameters would be scored. Both approaches signaled that a wide range of solutions would still be accepted, even those falling short of the highest rewards.

5.4.1.3 Subsume

With *subsume*, SMEs released solvers from incorporating either functions or designs in their solutions. While the SMEs discussed various important parameters during their formulation process, they did not incorporate all of them into the final problem statements. Instead, SMEs would subsume them: they architected *their* system to absorb or convert the range of solutions into those that met their needs. Because their architecture would absorb this variation, they could drop the parameter from the problem statement: assigning no score to it, removing penalties for not taking it into account, or omitting it entirely. Here, the contest's competitive nature informed SMEs' thinking yet again. Without a (meaningful) reward or penalty associated with that parameter, solvers would not (need to) incorporate this parameter into their design. Solvers would be free to make design choices as they saw fit. Subsume reduced the scrutiny that SMEs would give to a particular parameter, "[giving] competitors a chance to just have absolute design freedom," in the words of one SME.

SMEs discussed these parameters at length before deciding to apply this action. They determined that the parameters were, for example, "not viewed as germane to this contest." In their telling, the resulting rules then "dropped," "eliminated," or "didn't ask teams to account for" the parameters in question. SMEs also "lightened up" on parameters when they reduced their importance by shrinking their share of points. During the challenge, solvers would sometimes ask about the subsumed parameters. SMEs reminded them that these were not a required part of their design or that only "minor points" would be available. SMEs' language and responses to solvers drove home that, in their minds, this action would "give teams more flexibility" to create their solutions.

5.4.2 How did SMEs Choose each Action?

At the core of the formulation process, SMEs chose the action applied to each parameter based on their solution knowledge gathered through their expertise. Generally, when SMEs possessed more solution knowledge, they picked stricter actions, leading to rules with less flexibility for solvers—with few outliers. At the same time, the SMEs' knowledge of the solvers only played a role when they had the most solution knowledge. Namely, they only accommodated the solvers' estimated shortcomings when they knew what kinds of designs they wanted. We summarize these findings in the figure below.

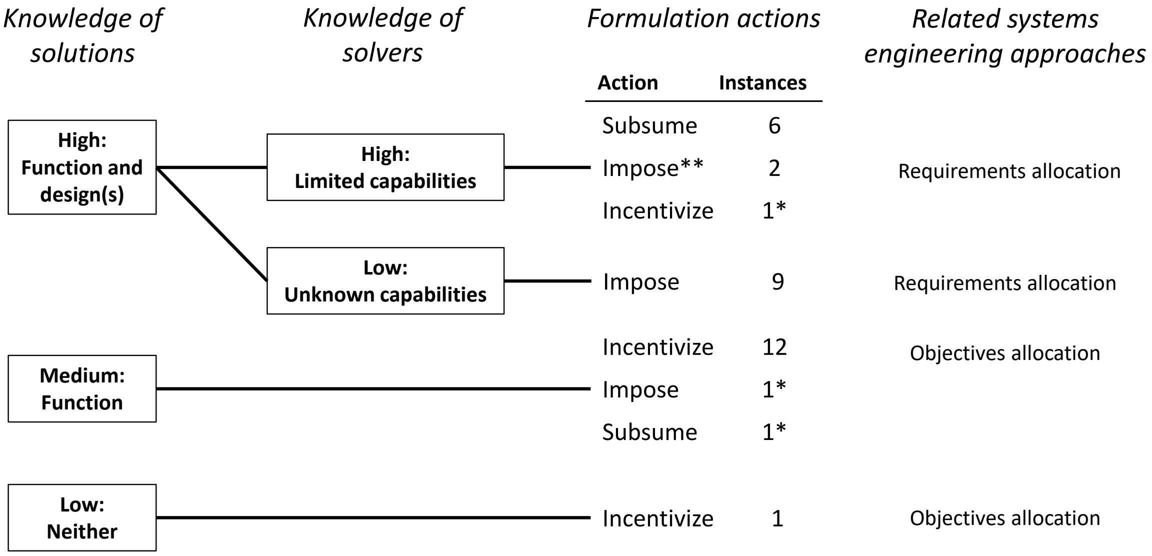

Figure 5.1: Actions Resulting from the Seeker's Knowledge of Solutions and Solvers

*: Outliers
**: The special case of *impose*, *best fit*

5.4.2.1 High Solution Knowledge

Knowing Both Functions and Designs When SMEs were confident about a design, they imposed it on the solvers' solutions. SMEs on the formulation teams had decades of experience in related topics—Mars' surface conditions and geology, human habitation in space, off-planet manufacturing and construction, and synthetic biology. For example, 3DPH SMEs built two in-house printers at two different NASA centers before the challenge started. These projects helped SMEs better understand the system's features like the timely deposition of the printer's feedstock and feedstock material choices. Based on their work, SMEs would derive design specifications[3] for specific parameters. For example, a habitat size of 1000 ft^2 to support a crew of four—any smaller, and the space would be less comfortable or less productive. Thus, they imposed these designs because, in their estimate, solutions that met these designs would address their need.

The SMEs' desire to incorporate these specifications into the rules of the contests was not surprising. If solvers were going to compliment SMEs' work, the contest would need to extend the knowledge they were building, sometimes continuing down a path that SMEs had already started down. The foundation that the SMEs had built would need to be translated into rules that solvers would follow. Solvers would then be armed with the same knowledge and face the same obstacles. For example, an SME on the 3DPH challenge formulation team described how they shaped the parameters concerning the printer's feedstock: "We were getting our needs put into the system there. We were saying, 'we need to make sure that the materials [the solvers] use are as relevant to planetary materials as possible.'" Thus, if the solvers' solutions did not follow the imposed designs, their solutions would fall short of addressing the SMEs' need.

The message to solvers was clear: comply with these rules or be disqualified. For example, SMEs imposed a minimum of indigenous Martian materials on the solvers' feedstocks. They based this threshold on in-house experiments that showed that while high, the threshold still produced a viable sample. Pursuing additive construction technologies means reducing NASA's launch costs: instead of bringing materials from

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[3] A design specification adds additional clarity to a functional one.

Earth, the crew would use those found on the planet's surface. When printing, using more local materials is better: high fractions of indigenous materials in the feedstock will negate the need for bringing these from Earth. The rules reflected this knowledge: solvers' feedstock recipe needed to meet (or exceed) a mass fraction of 70% aggregate[4] or be disqualified. Besides rules for the contents of the printer's feedstock, SMEs also imposed their knowledge on criteria like habitat area, life support systems designs, and printing specific complex shapes.

One outlier in this set was 3DPH Challenge's Phase 2 rules forbade physical interventions during printing operations. SMEs knew that autonomous operation of the printer—and by extension, limiting physical interventions—was extremely important to make the printing system work on Mars. At the time, no suitable autonomous systems had yet been developed for this application. Thus, the seeker knew what was needed, but not how the system could accomplish that. But SMEs believed that this was something that the solvers could achieve. Automated 3D printing at a desktop-scale was relatively common, and this was a similar problem to what the SMEs were facing. So, while the SMEs only knew the function that the system should address, they still imposed a strict design specification that did not allow any physical intervention during printing.

Impacts of Knowledge of Solvers' Capabilities While SMEs wanted to influence what kinds of solutions solvers would deliver, SMEs were also mindful of the effort required to create them. Converting CO_2 glucose and printing a Martian habitat were complex and new-to-the-world problems, with unique constraints. Finding people who had already solved the same problem in a different context— the easiest way to participate successfully —would likely be impossible. Solving the problem would require a development effort that many outside the space industry could not meet or afford—an uncertainty that would encourage shirking or discourage participation.

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[4] Described as a list of different rock types found on the surface of Mars by NASA SMEs.

SMEs expressed this concern in both challenges: while the specifications were important, what they were asking for “also [had] to be commensurate with the amount of money we’re offering and the timeframe we’re doing it in.”

To navigate this tension, SMEs chose two actions to create the problem statement: *best fit*, which was a special case of impose, and *subsume*. Both actions drew on their deep knowledge about the relevant parameter to accommodate solvers’ capabilities while progressing the technology past the “infant stage.” We explain both actions below.

First, *best fit*. Despite their confidence in a design, SMEs sometimes sought alternatives when they questioned the solvers’ capabilities to comply with what they required. This action was a special case of impose: it forced solvers to comply with designs that took their capabilities into account. Estimating that their intended designs would create a high barrier to entry, SMEs searched for easier, more accessible ones to mitigate the risk of getting few (or no) solutions. SMEs also drew on their knowledge for these designs, weighing them against what they thought could be achieved by solvers.

Best fit aimed to force solvers in the right direction, though they would not meet the SMEs’ goals. This action was, on its face, somewhat counterproductive to SMEs’ needs. SMEs lowered barriers to entry, making the problem more accessible. Yet, the incoming solutions would fall short and not fully address the SMEs’ need. Two arguments were made here. First, the specifics of the parameter meant solvers could avoid important technical questions if SMEs allowed a wide range of designs. Solution variety would be too risky as SMEs hoped to address these questions through the challenge—solvers would end up “[creating] a system that we couldn’t use.” Second, SMEs felt that partially meeting the need was better than not at all. They understood that tackling the problem statement would be an early step in the development process for these technologies. Even if these designs fell short of the need, they “felt like [these designs] would still push the technology, but [at a level] the people could actually do and have a chance at being successful at."

SMEs used this action in the 3DPH Challenge. For deployment on Mars, NASA needed printers to produce habitats that fit the crew's needs (approximately 1000 ft2). Printing at this scale would demonstrate that the team had overcome challenges not seen at smaller scales, like matching deposition and curing rates to avoid poor adhesion of layers. However, "building and demolishing a small, three-bedroom house [was] too much for everyone to handle," per the SMEs. In their search for easier designs, SMEs estimated that scaling the habitats' size down to one-third (approximately 100 ft2) would reduce enough of the solvers' costs to compete while still addressing (some of) the issues of printing at scale.

Second, subsume. When SMEs were confident about a design but questioned the solvers' capabilities to comply with them, they would sometimes omit—or subsume—a parameter from the problem statement. In their minds, solvers did not need to consider these criteria within the challenge. SMEs felt that the effort to comply with even partial designs would "overwhelm the whole thing and it would disperse the focus too much." Some SMEs also believed that these parameters were not the solvers' responsibility, and instead were "something that NASA owns at this juncture." Thus, by omitting any specification of these parameters, solvers could make design choices more in line with their capabilities. The slack in this part of the problem allowed them to focus their resources on other, and harder, parts of their solution.

How did the SMEs get the intended designs without explicitly asking for them? SMEs employed two approaches. First, they relied on solvers to find them organically. As described above, the SMEs had extensive knowledge of various parameters: what dynamics were at play and what functions and designs would address their need. In turn, both the 3DPH and CO_2 Challenges presented solvers with the same aims and similar dynamics and tradeoffs as the SMEs faced. Thus, SMEs hoped solvers would arrive at these designs as well. SMEs could then rely on their expertise to select the better solutions from the set.

The SMEs' second approach to subsume parameters would not leave this up to chance. As with the first approach, they would not include the parameter in question in the problem statement. But instead of compelling, nudging, or hoping solvers would produce the right designs, SMEs thought of ways to proactively integrate the ones they might receive into their systems. Doing so required extensive knowledge of that parameter and its dynamics. SMEs drew on their knowledge to estimate the range of designs they could receive *and* how they could convert that range to meet their need. Sometimes, converting the solution's output into a more suitable one required an add-on subsystem that provided the interface between it and the SMEs' systems. Other times, the solver's solution could reenter a known development process to convert it into one that met the need. Thus, SMEs took this action knowing that (nearly) any submitted solution could meet their needs; solvers did not need to be influenced. Instead, they could accommodate solvers' solutions by applying their knowledge.

The 3DPH Challenge presents an example of this approach. NASA takes the risk of fire in a crewed environment very seriously and has strict requirements for a material's flammability. Their standards would also apply here since these feedstocks would—ideally—be used to construct a crewed habitat. However, complying with these standards would be extremely expensive: non-NASA labs did not test to these conditions, and SMEs could not find a "good" best fit option. Instead, SMEs described their development plan in case the solutions seemed promising: they would "start an interchange" with the developer of an (otherwise) promising material to add flame retardants to its mix—an established process in spaceflight material development.

All but one of the subsume instances followed the patterns above. The purity of the sample in the CO_2 Challenge was an important measure of how well the conversion system would work on Mars: contaminants would spoil any downstream process using its outputs. However, SMEs could not settle on a purity standard to meet this need. Listing all possible contaminants was too onerous for SMEs to assemble, and existing purity tests would not be "even-handed" to all conversion approaches. Furthermore, SMEs believed that imposing *any* standard would distract teams, with their limited resources, from the goal of converting CO_2 to glucose. Instead, SMEs believed they would recognize what they would or would not deem acceptable. They also figured they could purify the output as an added step outside the challenge. So, while SMEs lacked a design for purity, they knew what they wanted and how to get it there, allowing them to subsume that criterion—fitting our established pattern.

5.4.2.2 Medium Solution Knowledge

When SMEs knew what a successful solution needed to do but not what design(s) could meet that, they *incentivized* those outcomes. SMEs' expertise dictated what functions would be crucial in developing a solution. A solution that lacked these functions would bypass important technical hurdles that SMEs set out to solve, resulting in a poor solution for NASA's aims. At the same time, SMEs acknowledged that further work was needed to find specific, suitable designs. Imposing their current estimates would likely result in premature or non-optimal solutions.

But despite this lack of knowledge, their expertise *did* inform what a better design entailed. For each function, SMEs could articulate their needs as maximizing, or minimizing, the relevant parameters: better solutions demonstrated more, or less, of a particular parameter. Even small steps in these directions would be desirable. To nudge solvers accordingly, SMEs chose to incentivize: they crafted a scoring gradient in the problem statement to match what kind of performance they wanted to see. SMEs hoped that the competitive aspects of the challenge would drive solvers to pursue that to the best of their capabilities.

For example, SMEs incentivized high yield strength of the printer's feedstock in the 3DPH Challenge. When NASA builds a habitat for its astronauts on Mars, the building (and its materials) must withstand a range of stresses. This range will depend on conditions on the surface of the planet (like surface gravity and wind loads). It would also depend on choices made by designers (like the habitat's shape), which are themselves influenced by the available printer and feedstock. At the time of the challenge, SMEs lacked the latter: they did not have an in-house design to estimate the loads that the materials needed to withstand—something they aimed to explore in the challenge. Lacking these details, SMEs proposed testing the materials' strength under compression and tension—one of several highly desirable characteristics. SMEs incentivized higher strength results to encourage solvers to design towards this aim. Moreover, the majority of the solvers' score depended on this parameter. The resulting rules were clear: while SMEs lacked a yield strength that the printed material needed to comply with for a potential habitat, the stronger the material, the better the solution.

In our data, only one instance did not fit this pattern. Here, SMEs incentivized solvers to explore designs when they were confident in a known design. In the 3DPH Challenge, some SMEs were quite certain that plastic-based feedstocks would be the best solution. They described its many benefits, including its printing performance in vacuum conditions: it maintains its structural integrity, unlike water-based feedstocks. In line with SMEs' confidence in their performance under vacuum conditions, early drafts of the rules only allowed plastic-based feedstocks in the challenge. However, SMEs decided to incentivize towards this function instead of compelling them to honor these designs. While some SMEs on the team thought this feedstock family might work best, others saw promise in other families as well. They believed exploration was crucial to develop suitable materials, and restricting solvers to one material family would severely limit it. The formulation team did not want to limit the exploration of different designs: they hesitated to force a solution they disagreed on. Per one SME: “We didn’t want to constrain them in any way possible. We wanted freedom of thought.” Thus, while we categorized this as an outlier, the pattern of imposing high-confidence designs and incentivizing needed functions remained.

5.4.2.3 Low Solution Knowledge

Lastly, when SMEs knew relatively little about addressing their needs, they incentivized design variety. There was only one instance of this implementation in our data: the architectural design of the habitat in the 3DPH Challenge’s first phase. Some NASA SMEs saw architectural design as an afterthought, wanting to focus on other aspects of the habitat. Others acknowledged, and were somewhat frustrated, that architectural design was outside the scope of their expertise and was generally lacking in-house: “How can you say that you’re going to develop [space infrastructure] without the help of architects to actually design it? It doesn’t make sense, it’s not correct.” The contest’s strategy would be to stress that NASA was looking for novel designs. Accordingly, the problem statement did not include functions or designs to guide solvers besides instructing solvers to use additive construction methods in their designs (in line with the contest’s theme). Here, the formulation team hoped that encouraging variety would reveal valuable solutions.

SMEs hoped solvers’ solutions would reveal valuable ones instead. The challenge’s problem statement and marketing campaigns heavily incentivized design novelty. Challenge representatives would tell potential solvers that they did not “want people to design a habitat that’s just square corners anymore.” Instead, the challenge urged solvers to search broadly as SMEs lacked an internal design or detailed function. By incentivizing novelty, SMEs hoped to encourage solvers to draw on their non-space expertise to create innovative designs. In addition to the designs themselves, SMEs would also acquire the functions that guided solvers’ efforts through the descriptions of their submissions. Thus, the relatively unconstrained search would reveal both designs and functions that SMEs could—and ultimately did—pursue in subsequent development cycles.

5.5 Discussion

In this paper, we explored the problem formulation process in crowdsourcing. Through our empirical work, we unpacked how the seeker translated their need into the problem statement for the solvers. Here, we found three actions that the seeker took to shape the solution space, thereby delegating the solving task to the solvers: impose, incentivize, and subsume. Motivating the seeker's choice between the three actions was the seeker's knowledge of potential solutions and solvers' limitations. In short, the more they knew what solutions would work, the stricter their decisions on the solvers' solutions space. Yet, only with the most knowledge of solutions could the seeker accommodate their (estimated) limitations. These findings overlapped with existing approaches to delegate solving tasks described in the systems engineering literature. Below, we discuss this connection. We also elaborate how insights from that literature can be extended to inform problem formulation in the crowdsourcing context.

5.5.1 Imposing Boundaries on the Solution Space

Impose—and, to some extent, *best fit*—mirrored the standard requirement allocation approach. In both cases, the seeker delegates the solving task by defining the range of solutions that are (un)acceptable (Vermillion and Malak, 2020). The seeker does so by imposing design characteristics on the solvers' solutions (Ryan and Wheatcraft, 2017). Communicating these design characteristics to others is relatively easy (Bijan et al., 2013), as they represent (easily) verifiable interfaces to the seeker's systems (Kossiakoff et al., 2011). The rigid boundaries that the imposed designs create narrow what solvers can explore: the seeker gave no leeway regardless of what kinds of solutions could result.

Like the requirement allocation approach, the seeker also used impose to influence the solvers' solutions. Usually, the seeker's need drives the selection of the required design characteristics (Ryan and Wheatcraft, 2017). By setting these requirements, they hope to spur the solvers to develop (a) solution(s) that addresses that need. The seeker in our context also considered this as a lever to drive development. The capabilities gained by imposing these designs often represented an advancement in the state of the art. For example, we described the design threshold of a minimum of 70% aggregate imposed on the 3DPH Challenge in Section 5.4.2.1. A high aggregate-to-binder ratio uses in-situ materials more efficiently. However, the threshold's design value can result in very brittle materials, which would perform poorly when printed. Still, the seeker forced solvers to overcome this new-to-the-world hurdle: developing a feedstock and related printing system that attained high efficiency while printing acceptably.

The systems engineering literature describes a key risk when implementing the requirements approach. In particular, scholars warn of bounding the wrong region(s) of the solution space (Malak and Paredis, 2009; Salado and Nilchiani, 2016). In our context, the seeker understood this risk as well. Being a team of experienced designers, they wanted to avoid specifying poor designs and "being too prescriptive," in their words. Thus, the seeker relied on their expertise to guide these decisions. They only imposed the interfaces with their (planned) systems—specific designs with high confidence that they would, or would not, work. This targeted implementation of impose left room to use the other actions for other parts of the problem—contrasting with the process laid out by the requirements approach. This way, they hoped to minimize the risk of excluding good solutions while curbing the search for underperforming solutions.

The overlap between our context and the insights in the systems engineering literature fell short at the best fit action. Recall that this special case accommodated solvers by imposing designs tailored to their capabilities, not what the seeker's expertise dictated. Here, the seeker deliberately imposed a "wrong" design—solutions that incorporated that design would not address their need. However, this action had a significant benefit. Compromising the design in these areas made the overall solution easier to create, while still maintaining some of its important elements. Thus, the action pushed solvers to search an area of the solution space that was acceptably inadequate in the eyes of the seeker. To the seeker, getting something that fell short in known ways was better than getting nothing.

5.5.2 Incentivizing Regions of the Solution Space

Incentivize mirrored the objective allocation approach advocated by scholars in the Value Drive Design community. In both cases, the seeker sets an objective as a goal, communicating their preference to the solver(s) (Hazelrigg, 1998). The incentive structure accompanying the objective motivates solvers to optimize their solutions accordingly (Collopy and Hollingsworth, 2011; Collopy, 1999). Solvers explore solutions along this gradient. It is up to the solver(s) to make design choices that (try to) achieve that goal (Vermillion and Malak, 2020).

Per the systems engineering literature, the objective allocation approach avoids the risk of setting poor boundaries described earlier (Collopy and Hollingsworth, 2011). In our context, the seeker followed this approach as well: applying the impose action when they did not know what solutions would work best. Specifically, they knew what function the solutions should accomplish regarding certain parameters, but not "how much" solutions should attain. Moreover, they did not know the combination of design choices that could perform well either. By incentivizing the function, they placed the risk of searching for and developing appropriate solutions on the solvers. Solvers would still be allowed to freely explore the solution space, but it was in their best interest to design with the seeker's intent in mind.

The seeker also used incentivize to drive needed development work as the objective allocation approach prescribes (Vermillion and Malak, 2020). The seeker identified the problem's "tall tent poles" and specified related functions for those parameters. They signaled the value of performing these functions (well) by scoring solutions based on their performance and heavily weighting this part of their score. The competitive nature of the contest raised the stakes for solutions to perform accordingly: poor performance would guarantee a loss.

One difference between our findings and the objective allocation approach was its implementation. Translating and allocating the objective function to each part of the problem is part and parcel of the objective allocation approach (Collopy and Hollingsworth, 2011; Lee et al., 2014). But the seeker in our context rarely decomposed their objective any further: partly because of their lack of understanding of its implications, partly in line with leaving design choices up to the solvers. Moreover, though the problem statement contained multiple incentivize rules, these were not carefully mapped to their respective parts of the problem. Thus, the seeker avoided a known concern for the objective allocation approach by not performing this mapping (Lee et al., 2014).

5.5.3 Subsuming a Variety of Designs

The subsume action did not mirror either of the systems engineering approaches. With this action, the seeker architected *their* system to absorb a range of solutions from the solvers. It obscured the seeker's intentions about the parameter in question instead of clearly communicating them like impose and incentivize did; the resulting problem statement specified neither function nor design. From the solvers' perspective, their freedom was total because the interface was hidden. Solvers would be able to make design choices that made sense to them (concerning the parameter in question).

Their apparent freedom of design lowered the barriers of the problem, thus facilitating their limits. From the seeker's perspective, they had to create an interface that could absorb a range of solutions. This was no small task. The risk of converting or absorbing this range rested solely on the seeker. As such, they only applied this action when they had high confidence in what good designs would be.

Besides high solution knowledge, the seeker's key question when implementing this action was: whose responsibility is this parameter? Through their expertise, the seeker knew of particular parameters unique to their context. They had faced these in previous designs, and had existing processes for incorporating these into designs. Because of their uniqueness, the seeker felt that any rules that forced or incentivized solvers to take them into account would be a significant burden. Thus, the action allowed the seeker to keep parts of the problem within their domain.

5.5.4 Contributions to Crowdsourcing

Organizations use crowdsourcing to search for novel and useful solutions to their problems (Terwiesch and Xu, 2008; Afuah and Tucci, 2012). This mechanism can gather a wealth of input from a wide range of contributors (Jeppesen and Lakhani, 2010; Szajnfarber et al., 2020) However, scholars have recently warned that too many solutions can have a negative effect on selecting good ones (Alexy et al., 2012; di Gangi et al., 2010). As more, and varying, solutions are submitted, the amount of information that the seeker needs to process to pick the best increases significantly. The seeker's attention is, thus, narrowed and they risk "wasting attention on the process of discerning good ideas from bad" (Piezunka and Dahlander, 2015, p. 876). Academic work has now focused on the problem's formulation as a way to influence solvers' exploration (Ehls et al., 2020; Wallin et al., 2018). In line with these streams, our findings show how the seeker can, usefully, narrow the solvers' exploration. Specifically, these three actions can tailor the solutions space according to the current state of knowledge: avoiding known areas of poor solutions but further exploring unknown ones. In short, an innovation contest—and by extension, crowdsourcing—can extend the search of the seeker in a more targeted way than has been previously described.

Our findings also present a different usage of innovation contests and the broadcast search mechanism more broadly. First, the seeker did not aim to maximize solution variety. The seeker deliberately narrowed the space of potential solutions to increase their likelihood of solving the problem. The more the seeker knew about potential solutions, the more they wanted to control the variety of solutions they received—solvers had less solutions space to search. This counters one of the longstanding benefits of contests: the seeker does not want maximum variety in the solutions (cf. Alexy et al., 2012; Terwiesch and Ulrich, 2009). This wastes the seeker's effort (Piezunka and Dahlander, 2015). But our findings show that the seeker did not want to waste the solvers' exploration effort either. Here, they solidified the high-confidence parts of the solution space and opens up more uncertain parts. Smart formulation strategies, like the seeker used in our context or "constraints that deconstrain" (Doyle and Csete, 2011), could direct the solvers' efforts more effectively.

Second, the seeker did not aim for the broadest possible participation. While the seeker can work to lower entry barriers, some must remain. Complex problems, even when decomposed, cannot be solved by everyone in a crowd. The combination of skills needed to solve the simply does not reside in a large swath of the population (Szajnfarber and Vrolijk, 2018; Szajnfarber et al., 2020). Additionally, many complex designs require design validation—demonstrating that a concept performs as expected is crucial to believe the solution. As such, the resources required to meet the needs are out of the reach of many—and may even prompt cost-benefit analyses within entities that can afford it. To get useful solutions, the seeker could identify domains that might provide good solutions and tailor the problem to attract its members. That way, their aim is useful depth instead of maximum reach.

5.5.5 Limitations

We set out to understand the formulation process for complex problems, which technical organizations often face. Our inductive approach captured the relevant dynamics that shaped the problem statements destined for an innovation contest. While the actions we mapped will be at the seeker's disposal across all formulation processes, the dynamics that shaped their choices might differ across settings. This limits where our insights can be applied.

First, our findings might not extend to settings where the seeker can iterate with the solver(s). Crowdsourcing represents a unique version of problem-solving, where the normal iterative process between seeker and solver(s) is interrupted (Wallin et al., 2018). In these iterations, uncertainties are addressed (Gralla et al., 2016): the solution space is clarified, the problem is reformulated, and the solving tasks are allocated based on the relative capabilities of those involved. Without these loops, the seeker might not understand the solvers' capability to solve the complex problem. This uncertainty induces the dynamics that we captured, thus impacting the choices on formulating the problem.

Second, our findings might not extend to settings with relatively simple problems either. In these settings, the solver's capabilities are not an issue. As such, its dynamics will also differ from our observations. Specifically, with little reason to account for this construct, the seeker might only shape the solution space by bounding and incentivizing parts of the solution space.

Chapter 6—Conclusion

Organizations are increasingly applying crowdsourcing to complex problems in the engineered systems contexts. With existing theory developed based on comparatively simple problems, it is important to extend theory to inform these kinds of problems as well. To this end, my work explored innovation contests challenging complex problems. Across the four essays, I described the relevant dynamics that help explain how to better implement this innovation tool. Below, I summarize how the essays collectively contribute to our understanding of complex innovation contests. Then, to help seekers improve their next innovation contest, I describe how to use these insights in practice. Lastly, I describe potential avenues for future work.

6.1 How the Dissertation's Contributions Change the View of Innovation Contests

My work contributes to a better understanding of innovation contests as applied to complex problems. Specifically, I counter the transactional view of the innovation contest—the brief interaction between the seeker and solvers that focuses on exchanging solution knowledge for the contest's prize, summarized in Section 1.3. Instead, this body of work describes a relational view of innovation contests. Innovation contests, especially ones that challenge a complex problem, are a prolonged interaction, with a rich exchange between those involved and pathways for crossovers. The contributions across the four essays inform the differences between the transactional view and the relational one, depicted in Figure 6.1. I describe these differences below.

First, Chapter 2 explored how the benefits of the complex innovation contest do not only materialize at its end. Instead, the seeker reaped both network and technology

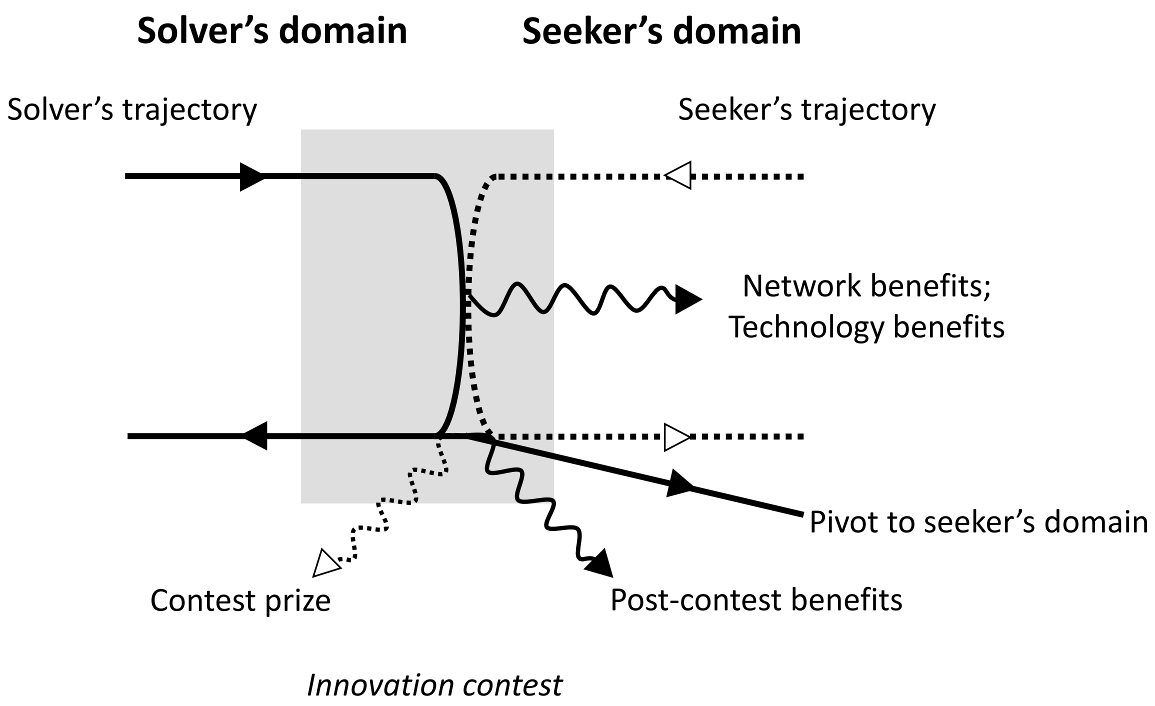

Figure 6.1: The relational view of innovation contests, which features a prolonged interaction and a rich exchange between seeker and solver(s)

benefits as the contest transpired, *including* the transfer of solution knowledge. The essay changes the location of the transfer in the diagram in Figure 6.1: from the contest's end to along its whole process. This difference emphasizes a holistic view of the contest—focusing on the benefits at the end ignores much of the seeker's potential value.

Second, Chapter 3 highlighted the opportunist solver archetype and their intent to pursue opportunities in the seeker's domain. This counters the prevailing view of all solvers returning to their baseline after the contest. For some, the seeker's need is not purely external. Instead, the contest overlaps with the solvers' (envisioned) technical trajectories and could "springboard" them to those outcomes. In that vein, access to the seeker's infrastructure and services was a significant motivator. After the contest, these opportunists continued their development activities within the seeker's domain. The essay adds a pathway for solvers in Figure 6.1: instead of only remaining in their domain, solvers can either return to their domain or continue in the seeker's. Additionally, Chapter 2 describes how opportunists' pursuits can be mutually beneficial in the long term: for example, partnering with the seeker to develop the focal technology further. These differences highlight a theoretical lever to shape the context around the focal technology, often crucial for its implementation.

Third, Chapter 4 explained that the problem's formulation is a shared task between the seeker and the solver(s). The problem is not thrown over a proverbial fence between domains. Instead, the seeker decides where the formulation resides in their overlap. The seeker also determines how free solvers are to reformulate the problem to search for relevant knowledge more easily. This essay highlights the overlapping space between the domains: I change the contest's depiction from a line in Figure 1.1 to a shaded area between domains in Figure 6.1. This difference allows the problem to be somewhere in the overlap between the two.

Lastly, Chapter 5 explored *how* the seeker formulated the problem. This is a difficult but crucial stage: as described in Chapter 2, it is a months-long, multi-stakeholder process. Per Chapters 3 and 4, the seeker's choices can influence who participates and how they see the problem. This essay unpacked how the seeker translated their need into the contest's problem statement: delegating the solving task and shaping what designs solvers would explore. Here, the seeker's solution knowledge and estimates of solver capabilities drove their choices to impose, incentivize, or subsume solver's exploration. While Chapter 5's contribution did not directly add to Figure 6.1, it emphasized that careful planning is needed to accomplish the desired outcomes.

Through these contributions, this dissertation extended the literature on crowdsourcing—and specifically innovation contests—to complex problems. My essays purposefully explored contests that challenged problems on engineered system design. With this focus, I created the relational view of innovation contests, which starkly contrasts with the longstanding transactional view that permeates the literature (see, e.g., Taylor, 1995; Fullerton and McAfee, 1999; Howe, 2006; Terwiesch and Xu, 2008; Morgan and Wang, 2010; Poetz and Schreier, 2012; Lifshitz-Assaf, 2018; Shergadwala et al., 2020).

The relational view extends our understanding in the following ways. First, the contest is more than a momentary transaction between seeker and solver. They can form strong connections that are maintained long after the contest is over: sometimes, they even form formal partnerships to continue the work begun in the contest. Second, solutions—and the knowledge contained within them—are not the only benefit the seeker can accrue. For example, these contests can foster an ecosystem of organizations and individuals that builds the knowledge basis for the technology in question. Third, the seeker is not the only one that formulates the problem: different stakeholders, including the solvers, can help determine what problem is solved. Fourth, the seeker and solvers are not the only ones that invest their expertise and resources: contest partners can help the seeker formulate both the contest and the problem, expanding the ecosystem that much more.

In summary, the relational view is how the traditional view extends into complex innovation contests. It more accurately reflects the contest's dynamics when applied to the kinds of problems that technical organizations face. It also clarifies important levers available for practitioners. In short, it is a new way to envision complex innovation contests.

6.2 Three Principles to Better Navigate Complex Innovation Contests

In this section, I frame insights from this dissertation in a practical light. Below, I describe five principles to help seekers address their complex problems using an innovation contest. These are not a set of directives. Instead, they highlight key issues to consider in their planning.

6.2.1 There is More to Gain Than Just Solutions

The solutions are but one benefit that an innovation contest can provide. Seekers should see the contest as a platform for a rich exchange of professional relationships *and* broader technical knowledge between themselves, the solvers, and contest partners.

The innovation contest attracts individuals and organizations from various domains. The significant influx of attention and resources to the topic is their signal to enter. These outsiders—be they (potential) solvers or contest partners—might see the contest as their opportunity to get involved with a topic they are personally, professionally, or organizationally interested in. Others might see the contest's non-traditional nature as a less formal way of interacting with the seeker. Specifically, the contest is a public-facing and gamified spin on the seeker's problem. Removing the formality of interactions can facilitate connections and conversations that would, otherwise, be more difficult to have.

The innovation contest forms or strengthens a dedicated ecosystem around the problem. The seeker, the solvers, and the contest partners build meaningful connections through the contest. And they maintain these relationships and their interest in the topic long after it is over. This resulting network, with its long-term focus and diverse efforts, can continue to build the knowledge base required to move the complex technology through its development and into deployment. Thus, the contest does not just attract outsiders to a specific topic. It *retains* them.

The innovation contest is also a platform to broadly exchange knowledge, not just to acquire solvers' submissions. For example, the seeker can access useful knowledge *before* the solvers submit their solutions. These exchanges happen, for example, in conversations with their external contest partners or Q&A sessions with potential solvers. Outsiders can help the seeker span multiple domains during the formulation stage, clarifying how existing solutions do–or do not—address their need. In turn, outsiders may get a better insight into the seeker's need and the technology being developed to address it.

While the solutions are *why* one would choose this tool to engage with outsiders, my work shows that contests have much more to offer.

6.2.2 The Contest's Structure and Problem can Influence its Outcomes

Carefully formulating the contest before its launch can increase the likelihood of desired outcomes. The innovation contest's open nature may imply that seekers should cast the widest net possible to find the one-in-a-million solution. In this framing, the seeker's efforts are focused on the contest's back-end: they filter through the (many) varied solutions to find the best one(s). My work balances that narrative, arguing that complex problems might require a different strategy. It shows why, and how, the seeker should focus their efforts on its front-end to achieve their aims.

The seeker has considerable influence on the contest's outcomes during its formulation. At this early stage, the seeker's choices influence both *who* responds to the contest and *how* they respond. Here, they can exert this influence through the contest's structure and problem. I describe two related sub-principles below.

In-kind Prizes Attract Some (Good) Solvers More than Money Regarding the contest's structure, different incentives can attract different solvers. Money is a common incentive for innovation contests. The monetary prize is readily understood, motivates effort broadly, and can be objectively valued. But non-monetary prizes can be an effective incentive as well. In particular, in-kind prizes attract solvers who want to pivot into the seeker's domain long term—in my data, most winners fell into this category. They see tremendous value in the prestige and recognition in developing the (winning) solution. They also see the value in focused (and closed-door) technology reviews by the seeker's experts. Or access to relevant equipment and infrastructure that is otherwise very costly or unavailable commercially. To them, these prizes may be more valuable than their equivalents in cash.

Using in-kind incentives can result in a more cost-effective contest. Specifically, holding the solver in high esteem or providing access to expertise and equipment might be relatively cheap for the seeker to provide—sometimes easier than money itself. This reduces the cost to set the prize yet maintains its value in the eyes of the solvers. Ultimately, a prize portfolio that smartly combines both monetary and non-monetary prizes leverages the incentive power of both at the same time.

Use the Problem's Formulation to Focus the Solvers' Efforts Translating a need into a problem statement can be daunting, especially for complex problems. Here, many different factors can influence the seeker's decisions, including the seeker's expertise, the resources they can dedicate to the contest, who they think should be responsible for different aspects of the problem, and (the seeker's estimates of) the solvers' capabilities. The concepts described in Chapters 4 and 5 can structure these complex decisions, helping the seeker navigate them successfully.

Specifically, the formulation bridge and the formulation actions guide how the solvers will solve. First, the bridge determines the amount of leeway given to solvers to approach the problem. An early handoff means more leeway: solutions are likely to be novel, but many will not be useful. It may also be hard to identify the good solutions without a lot of supporting information. A later handoff means less leeway: many solutions will be useful, and likely easy to put to use, but few—if any—will be truly novel. Second, the actions influence how solvers search for solutions. On a granular level, they determine the solvers' scope of the problem, acceptable kinds of solutions, and where new designs are needed. They do so by incorporating the seeker's knowledge and uncertainties of the solvers.

Problem formulation is a crucial step in the innovation contest process. The bridge and the actions structure key decisions in this stage, giving the seeker the tools to usefully focus solvers' efforts. Using these tools makes the complex process of problem formulation clearer and more efficient.

6.2.3 Tap Internal and External Experts to Shape the Contest

The seeker should rely on their internal experts during the formulation process. Their knowledge may be crucial to supporting the contest and framing a relevant problem. But at the same time, the seeker should not rely on them alone.

Input from internal experts is essential. First, their buy-in is vital for the seeker's organization to accept the contest as a worthwhile pursuit and a meaningful use of its resources. It may also help paint the contest as a valuable exploration of solution (and solution-provider) alternatives. With their buy-in, the contest might insulate itself from internal (and external) detractors. Second, their input on the problem can make absorbing the resulting solutions easier. For example, they can relay the interfaces that connect a solution to the rest of the organization's system. Without this input, a solution may have to be reworked to be infused.

But internal experts are not the only ones that can provide this support. The seeker can also tap outsiders—as either contest partners or (potential) solvers—to contribute to the formulation process. First, interested organizations or individuals may prefer to contribute as contest partners. Being involved as a solver—with its risk of losing to others—may not be worth the damage to their brand or the resources they need to commit to the problem. However, these outsiders might still want to get involved with the topic, especially if it aligns with future goals, opens up new paths, or helps them connect with the seeker. Benefits to the seeker include access to their domain knowledge, related person-hours, or specialized infrastructure. These help the seeker better formulate the problem and launch a bigger, better contest. Their assistance lightens the seeker's burden to achieve the same outcome. In return, the partner may enjoy the prestige of being a contest sponsor, the influence to (help) direct solving efforts, and the technical insights that come with reviewing the solutions.

Second, solvers interested in participating in the contest may *also* be interested in contributing to its formulation. Crowdsourcing is a tool to capture a large variety of inputs to a specific problem—it could also be used to capture input *regarding the problem itself* during the formulation process. Specifically, crowdsourcing the (re)formulation of the contest problem *before* it is broadcast for solving. This focused activity might reveal a problem suited to a broader range of domains and solvers. Or, conversely, it might reveal a reformulation of the seeker's problem in a particularly promising domain.

These outsiders add a valuable perspective to the seeker's formulation process. If the formulation is done solely by internal experts, there is a risk that they may define the problem too narrowly and suitable only for internal solving—much like the search for solutions. Here, outsiders' input may counter this risk by un-sticking the problem from the seeker's domain. Their input may even make the internal experts confirm their assumptions—a valuable exercise in a technical context. In short, while coming from different domains, outsiders' input may still reveal productive paths for the seeker's problem.

6.3 Future Work

In this section, I describe avenues for future research. I expand on my work's potential connections with studies on systems engineering, acquisition, entrepreneurship, and industry formation. This is not an exhaustive list. Rather, the insights in this dissertation pointed to these fields more than others. In the overlaps between these areas and my work, I can deepen and expand the contributions presented in this dissertation.

6.3.1 Problem-solving in Innovation Contests and Systems Engineering

Two camps in the systems engineering community have long been at odds on how to best delegate a solving task. On the one hand, the requirement allocation camp decomposes the solution space into regions of acceptable and unacceptable designs (Ryan and Wheatcraft, 2017). This explicitly limits what solutions are acceptable. On the other hand, the objective allocation camp communicates the design objectives that give the solution its value (Collopy and Hollingsworth, 2011). This nudges solvers towards more desirable solutions. Both camps have conducted extensive work to improve and expand (e.g., Suh, 1998; Salado and Kannan, 2018), or compare and contrast (e.g., Vermillion and Malak, 2020), the two approaches. But little regard is paid to the other's relative strengths.

My work, and others stemming from it, may help resolve this dichotomy. In my settings, the seeker—akin to the systems engineer—used actions that closely resembled these approaches. However, they used them at a more granular level than either camp describes. Additionally, they applied these (and other) actions to the *same* problem—in contrast to the mutually exclusive nature depicted in the literature. These findings create a space for new theory in systems engineering, where (similes to) the requirement and objective approaches can be used in a complementary manner. Follow-on studies may lead to insights on *how* the approaches can complement each other, leveraging the strengths of *both* when delegating a solving task to others.

6.3.2 Innovation Contests as an Acquisition Tool

Faced with a complex problem, a technical organization can rely on various tools to acquire a solution. In the open innovation community, the contest is widely regarded as a proven way to spur actors to solve a problem and gather their solutions (Terwiesch and Xu, 2008; Brunt et al., 2012). But more generally, it is far from the only mechanism that induces these efforts: grants, contracts, partnerships, and other traditional procurement methods accomplish this as well.

To integrate innovation contests into the procurement toolbox, scholars have identified several features that set innovation contests apart (Taylor, 1995; Fullerton and McAfee, 1999; Connelly et al., 2013; Terwiesch and Ulrich, 2009; Morgan and Wang, 2010; Murray et al., 2012; Szajnfarber and Vrolijk, 2018; Gustetic et al., 2015). First, their non-traditional nature and lower barriers to entry can attract a wide variety of solvers from domains that the seeker might not know. Second, this broad range of solvers competes to produce the best solution to the same problem, increasing the chances of finding a high-value, outlying solution. Lastly, the seeker measures solution performance—and determines the winner—at the end of the contest. This way, they do not need to continuously monitor the quality of the solvers' efforts. With the acquisition process facing the risks of optimistic cost estimates and the burdens of oversight (Brainard and Szajnfarber, 2019; Brainard, 2018), these describe a compelling addition to an organization's toolbox.

But how to pick the right tool for a particular problem is still an open question. First, unlike the other procurement mechanisms, organizations still regard innovation contests as a special activity (Gustetic et al., 2018), often requiring new organizational strategies or policies to implement (Füller et al., 2021). Second, and relatedly, overcoming internal hesitation to launch a contest requires the "education" that the contest is "less of a niche or gimmick" (Shergadwala et al., 2020, p. 7), which is not the case for the other tools. Third, only a handful of studies have directly compared innovation contests to other mechanisms. Some explore when a seeker would choose one mechanism over another (Afuah and Tucci, 2012; Lakhani et al., 2013c). Others compared the costs of the innovation contest to a procurement of the same size (Paik et al., 2020). But much like the innovation contest literature more generally, these studies tend to focus on contests challenging simple problems. In short, much scholarly work is still needed to know how to fully integrate contests into an organization's procurement toolbox, where it can easily choose the best tool(s) for the job.

With technical organizations increasingly launching innovation contests, especially for complex problems, we need to better understand its place within the toolbox. In this dissertation, I make small steps in that direction. My work described the range of benefits that the innovation contest's seeker can accrue, clarifying the value that the host organization receives. It also highlighted how the contest can reflect the seeker's knowledge of the topic and their uncertainty of the solvers' capabilities, clarifying its strengths in delegating the solving task. These insights shed light on important aspects of this tool. They help enable future studies to better compare it to the traditional procurement mechanisms, producing policy insights that practitioners could directly use in their programs.

6.3.3 Innovation Contests as a Platform for Entrepreneurship

Entrepreneurs play a key role in shepherding technological changes into the market(s) (Drucker, 1985). Recognizing this importance, scholars have focused their research on the causes of entrepreneurship (Venkataraman, 1997; Shah and Tripsas, 2007), its effects (Santos and Eisenhardt, 2009; Agarwal et al., 2017), and its interactions with new mechanisms of technology development—including open innovation (Eftekhari and Bogers, 2015).

Despite this ongoing work, the interaction between entrepreneurship and innovation contests is not well understood (Bogers et al., 2017). Specifically, we do not understand how and why solvers leverage their participation in the contest into an entrepreneurial opportunity. When they participate, the solver addresses the seeker's (now public) need, with many others creating technology to serve the same function. The resulting solution is not an endogenous discovery, nor does it stem from their employment or personal hobby. Yet, solvers still decide to start a new venture based on their participation. The existing literature on entrepreneurship does not fully explain this pathway (Shah and Tripsas, 2007, 2016). The mechanisms that facilitate the solver's transition from contest participant to entrepreneur are also not understood (Kay, 2012).

My work shed light on entrepreneurship in innovation contests. I showed how (budding) entrepreneurs used the contest as a springboard to new opportunities and markets—sometimes within the seeker's domain, sometimes within their own. Importantly, they were not always ad-hoc decisions; the work they would need to accomplish in the contest dove-tailed with their technology's planned trajectory. I also showed why in-kind prizes are a stronger incentive for these entrepreneurs to participate: these kinds of prizes better support their trajectories. These findings can help build new theory that links entrepreneurship and innovation contests—theory that is much needed. Innovation contests are being launched to spur entrepreneurial activity: government agencies like NASA and the U.S. Department of Energy (DOE) expect new ventures out of their respective innovation contests. A better understanding of these dynamics might help shape and strengthen the innovation contest as a tool of industrial policy.

6.3.4 Innovation Contests as a Catalyst for Industry Formation

Scholars describe innovation contests as (one of several) potential catalysts for an industry's incubation period (Agarwal et al., 2017; Moeen and Agarwal, 2017). Here, they describe the clear signal of a niche interest given by the seeker; solvers respond by self-organizing and moving resources and knowledge to fill the stated need. For example, the Defense Advanced Research Projects Agency's Grand Challenge series is widely regarded as *the* spark for the autonomous vehicle industry (Anderson, 2019). Its solvers and their work were crucial to Google's self-driving car team, navigation sensor development, and U.S. Department of Defense's autonomous ground vehicle capabilities (Stine, 2009; Davies, 2017). But *how* the innovation contest catalyzes a new industry is not well understood.

Here, my work sheds some light on these dynamics. Specifically, the introduction of the contest spurred long-term technology development activities in a focused manner. These activities advanced a technology of interest and established crucial communication lines among those with related expertise. Some solvers invested their resources and attention with an eye towards the long run—the knowledge and networks they helped create only strengthened after the contest. Additionally, the volume of activities and resources committed to the topic would not have occurred without the contest. These findings begin to show *how* a contest can stimulate the activities necessary for industry formation, adding to the respective literature.

During the incubation period, technical, contributor, and demand uncertainties are addressed, moving the emerging industry's state-of-the-art forward (Agarwal et al., 2017). Innovation contests can address these uncertainties too. Below, I further describe how a contest can trigger the formation of new industries.

Technical uncertainty During the incubation period, various actors try to understand how the focal technology will work. Its basis of knowledge is not yet established, and how this basis interfaces with—or displaces—existing knowledge is still an open question (Helfat and Lieberman, 2002; Moeen and Agarwal, 2017; Moeen et al., 2019). The technology's form is also yet to be determined (Ulrich, 1995). Thus, actors' technical choices during this period matter greatly: development successes are likely to impact the technology and its industry (Anderson and Tushman, 1990).

In my settings, the seekers required solvers to demonstrate physical prototypes of the core systems—not just solvers' concepts. This forced them to develop high-scoring designs and overcome their implementation's hardware (and software) challenges. In all, these efforts helped demonstrate that their designs worked as intended. With the inherent benefits of multiple and varying attempts at the same problem (Tuertscher et al., 2014; Pirtle et al., 2018; Szajnfarber and Vrolijk, 2018), the seeker was confident many aspects of the winning designs and even adopted their design choices in-house.

Contributor uncertainty During this period, actors also establish *who* will provide the relevant technical knowledge (Agarwal et al., 2017; Shah and Tripsas, 2007). Both complex and novel problems may require new perspectives to solve the problem, as experts within their domains may be unable to pivot to new views and approaches (Cañas et al., 2003; Bilalić et al., 2008). As such, identifying who will be best suited to provide the right knowledge is difficult (Afuah and Tucci, 2012; Franke et al., 2013). Furthermore, if these identified individuals are to contribute on an ongoing basis, the switch from their industry to the focal one will (likely) come at a high cost (Myers, 2020).

Acting as a North Star, the contests attracted various individuals and organizations. These spanned different industries and contributed to the topic in many different capacities. Instead of the seeker searching for the appropriate expertise, the contests presented a roster of potentially useful contributors. In addition to displaying their knowledge, it also showed *who* was willing to get involved in the focal technology for the long-term, overcoming the substantial costs of creating a foothold in a new industry.

Demand uncertainty Lastly, the various actors also try to address uncertainties related to the technology's commercialization during the incubation period. In general, they are looking to answer the question "will it sell?" (Shane and Venkataraman, 2000; Shah and Tripsas, 2007). Here, they explore how the technology may serve particular markets (Shane, 2000; Agarwal et al., 2017), how to build legitimacy for a venture among potential buyers (Aldrich and Fiol, 1994), and how to make the right choices on the organization's structure and boundaries (Santos and Eisenhardt, 2009). Progressing these questions is crucial to evolving past incubation and into commercialization.

In my settings, the seeker addressed this question in two ways. First, they would sometimes create the demand themselves. In these cases, they would use the contest to search for a future service provider, preferring to "just buy this capability and not have to work on it." Second, the seeker would sometimes tailor the contest to other potential markets, not just their technological needs. They also recognized that widespread adoption of the core technology would make it more robust for their applications. Thus, they sometimes envisioned how it could function in other settings. In these cases, they would try to bridge the technology's market opportunities with the technical specifications set in the contest. By bringing these two closer together, they would vet how ready the technology demonstrated in the contest was for "primetime."

As summarized above, my work provides preliminary evidence to show *how* these complex innovation contests can catalyze an industry. This creates an early link between empirical data on innovation contests and the industry formation literature—one that future studies could continue to explore and strengthen.

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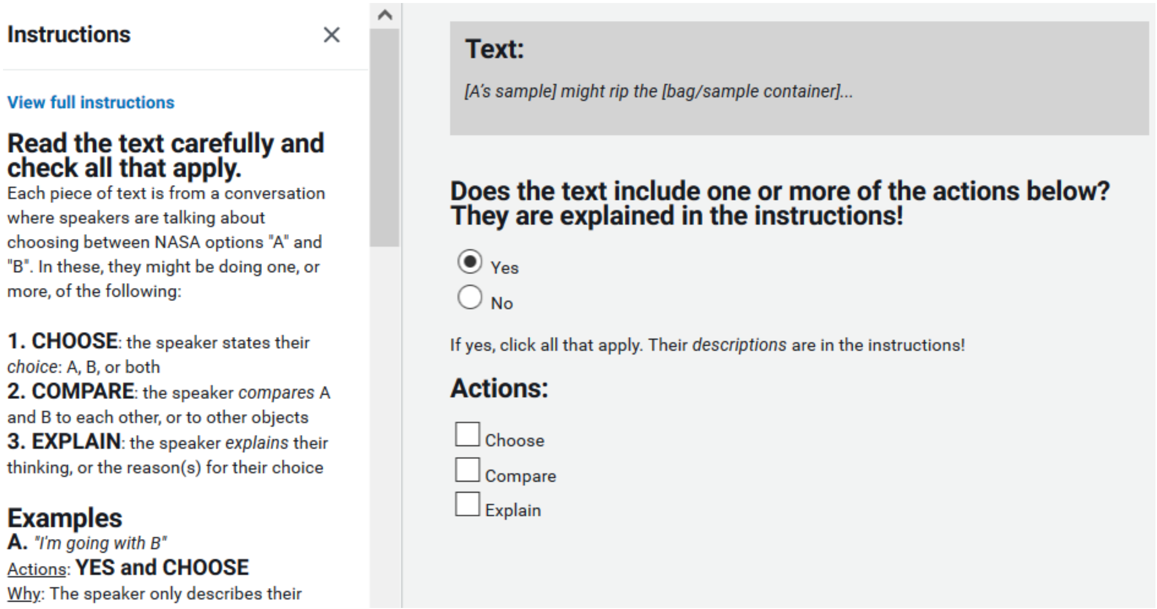
Appendix A—Coding on Amazon Mechanical Turk

To code the participants' contributions that we identified in the discussions, we created two coding tasks on the MTurk platform, one for each dependent variable. As an MTurk Requester, we created these to match similar tasks on the platform. Each Human Intelligence Task (HIT) contained a brief description of the context, the coding task, further explanations of the categories, and relevant examples from the data, laid out in a manner suited to what the workers would expect.

To facilitate coding on this platform, we structured the coding tasks as follows. The worker would answer "yes" or "no" to "Does the text include one or more [choices] below?" We employed this to mitigate workers randomly selecting options to complete the task quicker. Clicking "yes" unlocked the relevant choices. Once the worker's choices were selected, they pressed "Submit" to finalize the HIT, and proceed to the next one. In Figure A.1 and Figure A.2 below, we show screenshots of the HIT interface that we created for our data. In the former, short instructions (left) appeared alongside the task and choices (right). We also included five coded examples (A through E) from our data to guide workers on this task (bottom left). In the latter, we included background on the context and a further explanation of the coding choices.

A total of 66 anonymous Master Workers coded our data. According to the MTurk platform, these workers are given this qualification for having "consistently demonstrated a high degree of success in performing a wide range of HITs across a large number of Requesters" (Amazon Mechanical Turk, 2018). Drawing on previous studies that used MTurk workers as coders (see also van der Boor et al., 2014; Xiao et al., 2018; Zhang and Chen, 2019), we required each contribution in our data set (438) to be coded seven times per dependent variable. These 6,132 data points were



Instructions ×

View full instructions

Read the text carefully and check all that apply.

Each piece of text is from a conversation where speakers are talking about choosing between NASA options "A" and "B". In these, they might be doing one, or more, of the following:

1. CHOOSE: the speaker states their *choice*: A, B, or both
2. COMPARE: the speaker *compares* A and B to each other, or to other objects
3. EXPLAIN: the speaker *explains* their thinking, or the reason(s) for their choice

Examples

A. *"I'm going with B"*
Actions: **YES and CHOOSE**
Why: The speaker only describes their

Text:

[A's sample] might rip the [bag/sample container]...

Does the text include one or more of the actions below? They are explained in the instructions!

● Yes
○ No

If yes, click all that apply. Their *descriptions* are in the instructions!

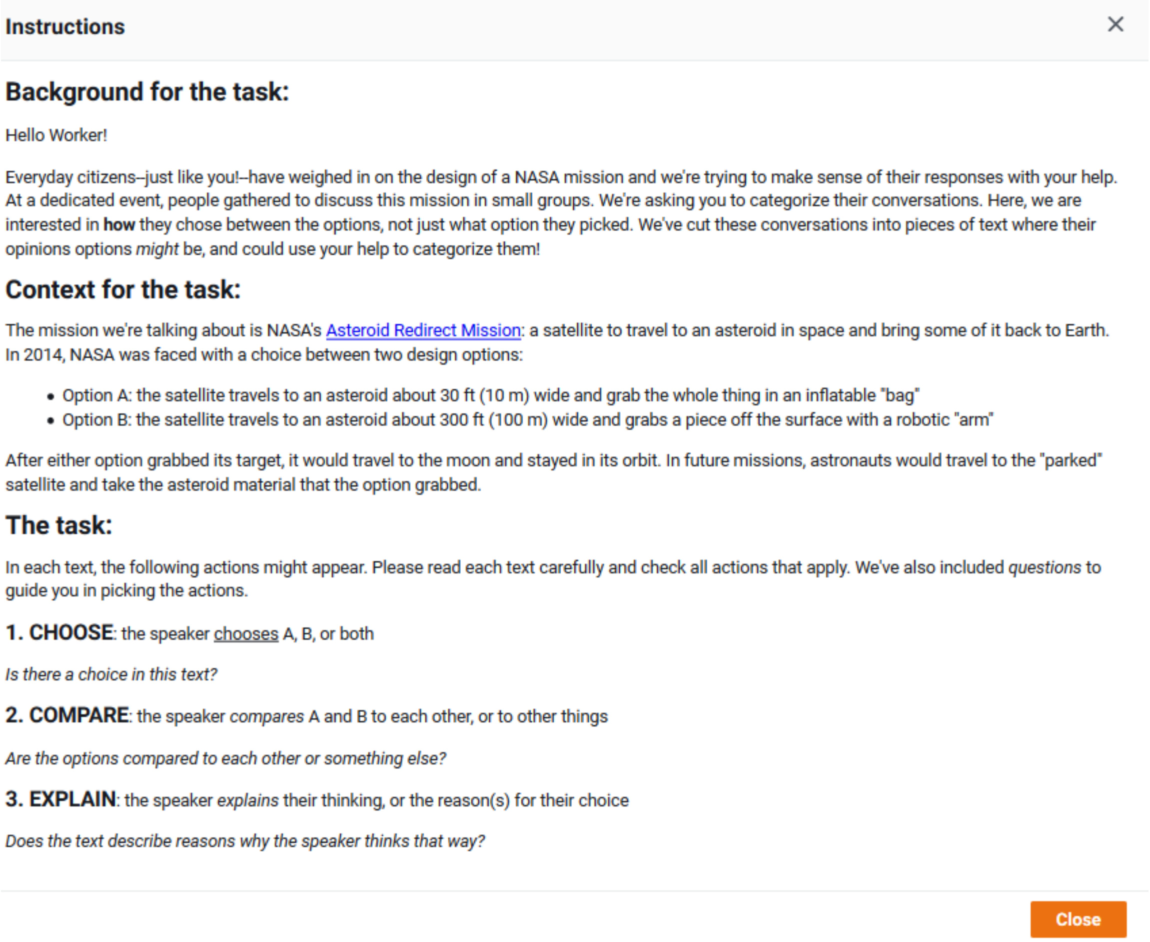
Actions:

☐ Choose
☐ Compare
☐ Explain

Figure A.1: Coding Interface for MTurk Workers

coded by 66 unique workers. They coded between 1 and 700 HITs each, where the median was 12. The workers were paid \$0.07 per HIT coded. This is on par with US average minimum wage (U.S. Department of Labor, 2009) for the estimated duration of each task as measured by the research team.

We set a threshold for agreement of six (or more) workers out of seven agreeing, or an interrater agreement greater than 86%. We applied this threshold on the first part of the coding task—the yes-or-no question—for both dependent variables: i.e. it was coded as "yes" only if six or more workers agreed. To ensure the robustness of the results, we also ran our models at an agreement level of at least five workers out of seven (greater than 71% agreement). We report these results where appropriate. The amount of knowledge transferred in each contribution (an ordinal measure), required further calculation. Here, we calculated the simple majority of the "yes" votes among the three choices of "choose," "compare," and "explain."



Background for the task:

Hello Worker!

Everyday citizens--just like you!--have weighed in on the design of a NASA mission and we're trying to make sense of their responses with your help. At a dedicated event, people gathered to discuss this mission in small groups. We're asking you to categorize their conversations. Here, we are interested in **how** they chose between the options, not just what option they picked. We've cut these conversations into pieces of text where their opinions options *might* be, and could use your help to categorize them!

Context for the task:

The mission we're talking about is NASA's Asteroid Redirect Mission: a satellite to travel to an asteroid in space and bring some of it back to Earth. In 2014, NASA was faced with a choice between two design options:

- Option A: the satellite travels to an asteroid about 30 ft (10 m) wide and grab the whole thing in an inflatable "bag"
- Option B: the satellite travels to an asteroid about 300 ft (100 m) wide and grabs a piece off the surface with a robotic "arm"

After either option grabbed its target, it would travel to the moon and stayed in its orbit. In future missions, astronauts would travel to the "parked" satellite and take the asteroid material that the option grabbed.

The task:

In each text, the following actions might appear. Please read each text carefully and check all actions that apply. We've also included *questions* to guide you in picking the actions.

1. CHOOSE: the speaker chooses A, B, or both

Is there a choice in this text?

2. COMPARE: the speaker *compares* A and B to each other, or to other things

Are the options compared to each other or something else?

3. EXPLAIN: the speaker *explains* their thinking, or the reason(s) for their choice

Does the text describe reasons why the speaker thinks that way?

Figure A.2: Full Instructions for MTurk Workers

Appendix B—Formulating the CO_2 to Glucose Challenge

This appendix summarizes the formulation process of NASA CO_2-to-Glucose Challenge. It highlights the important decisions that shaped the problem that participants would solve when they competed. These decisions were primarily made by NASA's subject matter experts in related fields of CO_2-based manufacturing. This document also summarizes the Challenge's outcomes viewed through the formulation lens.

The Challenge aimed to find and demonstrate an efficient pathway of converting CO_2 to glucose, a conversion that would be highly valuable during long-duration stays on Mars. The challenge launched in 2018 and ended in 2021.

B.1 NASA's Technology Goals

B.1.1 Using CO_2 as an In-Situ Resource

NASA plans to land astronauts on Mars in the 2030s. This is an expensive endeavor especially considering the infrastructure and consumables needed to keep the crew alive. To address this issue, subject matter experts (SMEs) across the agency are investigating how resources on Mars could be used to create the needed products instead of transporting them from Earth. These systems would reduce the launch costs and provide the crew with a degree of self-sufficiency [CO1].

CO_2 could be a critical Martian resource for this endeavor. During their stay, the crew will need organic consumables like pharmaceuticals, nutrients, adhesives, and fuels [CCP149, CO3, CO1]. Here, the carbon atoms in CO_2 can form the building blocks for these products. SMEs at NASA Ames—drawing on their expertise in synthetic biology, regenerative life support, and CO_2-based manufacturing in the space context [CO3, CO23]—propose engineered bacteria to convert the CO_2 into those products [CO1, CO3]. These bacteria will need a source of energy, and glucose—itself an organic compound—is one of the best candidates for their "food" [CO1, CO3, CO4]. As such, the ability to convert CO_2 into glucose—and other valuable sugars—is a useful capability: it can enable the crew to create various complex products locally.

B.1.2 Developing Efficient Pathways to Convert CO_2 into Glucose

At a high level, the design of a CO_2-to-glucose conversion system involves two questions. First, how will this system fit with NASA's (planned) Mars infrastructure [CO23]? The space context imposes constraints on any technology, and this would be no exception. CO_2 manufacturing SMEs describe two important parameters at this early stage of development [CO23]. First, volume. If the conversion system were the size of a room, it would not be feasible [CO22, CO23]. Second, power. If the system required megawatts of power to operate, it would not be feasible either [CO23]. So, the system's implementation on Mars imposes limits that need to be taken into account.

Second, what conversion method will the system use? A bioreactor *could* perform the function of turning CO_2 into glucose. In fact, a biological approach would be easier: producing glucose via plants, microorganisms, or enzymes is common in various industries [CO2]. And organisms can, likely, be engineered to perform this task by leveraging other technologies like CRISPR and gene editing [CO23]. However, any biological system has drawbacks that make it a less desirable option for Mars[1]. First, they are large: the system needs large tanks with liquid for the organisms in the reactors [CO23]. Second, they lag: starting and stopping the organisms from producing their products can take a lot of time, which means that controlling the process is difficult [CO3, CO23]. Lastly, they are fragile: the reactor's conditions need to be

---

[1] Note that the crew would still need bioreactors, and associated bacteria, to manufacture the more complex products. But reducing this system's footprint by reducing its dependence on biological approaches was considered valuable.

closely controlled to keep the organisms alive [CO3]. Faced with these drawbacks, the SMEs wanted to try a different approach for producing glucose.

Specifically, the NASA SMEs wanted to know whether a physiochemical system would be feasible. Such a system would be very valuable: compact, fast, efficient, responsive, and robust [CO3, CO4, CO23]. One SME succinctly described how he thought a hypothetical system would look like:

> It would be a single or two-step process with little to no waste. Incredibly efficient in terms of bond breaking— The energy needed to break and make bonds. And [it would be] highly reliable, doesn't ruin your catalysts, and doesn't get really dirty and you need to wash the whole thing with an acid. [CO22]

But this approach had its own risks. Previous work has shown the conversion of CO_2 into other carbon molecules, but only into products with less than six carbon atoms—which glucose has [CO12]. Additionally, any conversion from one molecule to another requires more and more energy. So, while the SMEs acknowledged that a "college student" could "hopscotch" their way from CO_2 through the different intermediate products to glucose [CO10], finding a pathway that's efficient and not wasteful was the big issue. Additionally, physiochemical conversion was many people had researched or implemented [CO24, CO2]. For Earth applications, one does not need bacteria food from CO_2—there are many cheap, biological sources for this [CO2, CO3]. Per one SME: "very few people have done anything of strong significance. It's all very new" [CO3]. As such, the approach would be "extremely hard" [CO23, see also CO26] but also "not economically favorable" in the SMEs' eyes [CO3].

B.2 Opening the Conversion Problem

B.2.1 Betting on Different Approaches and Outsiders

There were less risky options to feed bacteria for NASA's aims—both in approach and product. Converting CO_2 into bacteria food is a complex problem [CO3], and SMEs considered solving it through their regular innovation or problem-solving funding channels. But they would only be able to make "some incremental changes" through these channels with known players [CO23]. For example, while glucose is "the gold standard" for energy for bacteria, other products could perform that role as well [CO10]. Among these, acetate is "one of the better products" [CO10]. But this is a tradeoff between performance and uncertainty. Acetate contains less energy than glucose, which means it is not as good a food source. However, it is easier to convert from CO_2: there is less uncertainty in pursuing the acetate route. Thus, acetate would be a "very likely outcome that we can use, versus [glucose,] an unlikely one that would be great if it did work" per one of the SMEs [CO10].

Nevertheless, SMEs decided to bet on *both* acetate's safe bet *and* the glucose long shot—forming a "suite of approaches" to address this problem [CO23]. The same SMEs started a "collaborative agreement" with a lab at Stanford for the former [CO3]. The external partner chased the acetate conversion, and has since broken records for efficiency and yield [CO10]. Separately, a collaboration of several universities and institutes began working on interrelated biomanufacturing projects, including the CO_2 to acetate pathway. Led by UC Berkeley, they won a multi-year, multi-million-dollar NASA grant to do this work [CO10].

For the latter, the SMEs wanted to try something different. Here, SMEs decided that a challenge would be an appropriate avenue for this problem for several reasons [CO3]. First, while the function of converting CO_2 into usable products was not novel, no one had yet developed a physiochemical pathway of doing this efficiently. SMEs knew they needed to push the field in the direction of converting CO_2 to glucose, encouraging or incentivizing the right people and their institution. They hoped to jumpstart widespread commercial activity on these kinds of conversions [CO3]. Second, SMEs did not know who may have had a potential solution to this problem. CO_2 conversion is a nascent field; people with relevant expertise could have been in a "business, or within the academic realm, or wherever" [CO3]. A challenge would reach more people (and organizations), especially those "not traditionally part of the NASA stakeholder base" [CO23]. Third, SMEs wanted to encourage momentum behind the problem that would sustain it "financially, legally, [and] politically" [CO23]. A challenge would connect to the public, shine a light on the issue, and get interested parties to form a long-term ecosystem around it [CO3, CO23]. SMEs expected solvers to "become part of [the] journey [and] come along with [us]" [CO23]. So, high-level discussions at NASA headquarters decided to go the open innovation route [CO2], and "throw the challenge out to the world and see who's been thinking about this" [CO3].

While the challenge would reach people people "from everywhere" [CO23], SMEs did not expect whomever to solve this problem [CO2, CO23]. They had a set of people in mind that had a better chance of solving it. These were outside the aerospace industry and, predominantly, in green chemistry:

> People in the green chemistry arena, we think, will be the most interested in this. We've reached out to several companies. If you look, there's kind of an XPRIZE challenge right now, using CO_2 as a resource. It's a much larger and less pointed challenge than what ours is. People within that realm of expertise. There are [the] Green Chemistry societies— It's chemical engineers, particularly people who are looking at CO_2 conversion technologies [CO2].

The SMEs' betting strategy was about spreading the risk and maximizing the chances of success. Funding the partnership on acetate was very likely to yield good results. But there would be a chance that the challenge would make some progress as well. They could incorporate this pathway into NASA's regular innovation channels if it did. One SME described how that would occur:

> Now that being said, if anyone in the challenge starts to make this in a decent way and– And it's not a guarantee, I'm just saying that it's possible that we could look at the winner or winners and we could say, "gee, we would like to help you keep moving forward on that." Find a collaborative way to keep moving forward on that as well. [CO10]

B.2.2 Scoping the Challenge's problem

After deciding to pursue a challenge, SMEs' next hurdle was scoping the challenge problem. Deciding on the challenge problem and how to measure its solutions was not easy [CO33]. This process included several teams: HEO Advanced Exploration Space (AES), NASA Ames, the CCP, and ad-hoc input from SMEs at DoE and National Academy of Sciences [CO4, CCP149]. Here, NASA's senior SMEs on the topic held the most sway in these decisions. They "[would] drown out other voices" in this discussion [CO25], ensuring that the challenge would be in line with the technical direction they believed was most promising.

To make sure the problem was possible at all, the SMEs relied on first-principle calculations and previous work done by NASA and others. They started their scoping by calculating what manufacturing rates of glucose were theoretically possible under the conditions imposed by the hypothetical settlement on Mars. These would dictate the order of magnitude for the system's footprint: how large the system would be and how much power it would need [CO23]. They also compared these estimates to conversions to intermediate products to gauge whether they were in the right ballpark [CO23]. These were all to ensure that the problem was not physically impossible from the outset. If it exceeded the size and power upper bounds by a lot, then it would not be a good path to pursue.

With the feasibility of the problem established, formulating a feasible challenge was the next task. There were three aims that the SMEs were trying to balance: addressing NASA's need, encouraging non-traditional activity on this topic, and judging solutions both fairly and accurately [CO2, CO3, CO23]. The need to balance these three had a profound impact on the challenge problem.

B.2.3 Focus Areas for the Formulation Process

B.2.3.1 The Challenge's Deliverables

With these aims in mind, SMEs considered what solvers would deliver in response to the challenge. Their initial idea was to ask solvers for a "plan" to create the conversion system [CO3]: requiring a description of their pathway from CO_2 to glucose, with the appropriate analysis to back that up.

Initially, this deliverable was suggested *instead* of going directly to a (prototype) production system [CO3]—what SMEs wanted in the first place. SMEs thought people or organizations with little background might want to give the challenge a try. And since there would not be a way to transport the reactors to one NASA site, the judges would potentially have to spend resources to "[go] to places or [deal] with products that are just not ready for primetime" [CO3]. "That can create[d] an administrative burden" that they did not want to bear, per one SME [CO3].

However, this deliverable would only resolve so much of the uncertainty of the solution; it did not demonstrate that the solver's plan could actually work [CO10]. As with the hopscotch example, people could describe pathways that make sense on paper. But a paper solution alone would leave much of the implementation uncertainty unaddressed [CO22]. SMEs mentioned several issues that could differ between plan and demonstration: uncertainties, and limits, in the workings of different catalysts; micro-interactions of compounds creating unwanted products; changes in system behavior with temperature changes and or the presence of oxygen; and uncertainties in behavior depending on *how* materials are introduced in the reactor [CO3, CO22]. In short, describing the pathway and its system would show promise and build confidence in the approach, but a demonstration would resolve much more of its uncertainty.

SMEs decided on two competitions: the first to plan the conversion system (Phase 1) and the second to build it (Phase 2). In addition to the uncertainty around the quality of the solutions, having to self-fund the whole problem would be expensive per the SMEs [CO3]. Having two separate competitions gave SMEs an opportunity to award a (small) prize to the plans that looked the most promising [CO3]. This would give a leg up to solvers who might not be as well funded as other teams but still might have solid ideas for solving this problem [CO3]. A two-phased challenge also would provide a gate to screen for solution quality and teams' technical abilities in the first round [CO12]. Thus, both sides were primed for a more complex second phase: SMEs, through a better picture of the participants and their solutions; and solvers themselves, through their work on their plans. With the difficulty of the conversion problem in mind, SMEs wondered who, and how many, would show up to solve the problem: "if they're heavily funded large industries or if they're academicians or small start-ups" [CO3]. These discussions also involved the challenge requirements, which could have influenced participation: e.g., the mass and phase (solid or liquid) of the sample and the footprint of their system [CO9]. CCP would release the challenge phases in a staggered manner: Phase 1 on its own and Phase 2 at a later date.

To better understand the operation of the solvers' systems, judges would conduct site visits in Phase 2. SMEs expected the challenge systems to be "large and complicated" [CO12]. Unlike other Centennial Challenges, transporting these to a central location might not be feasible [CO12]. Instead, the challenge judges would fly out for a site visit, seeing the solvers' operation and output in person [CO12, CO4]: During this visit, solvers would have up to seven hours—the estimated maximum length of the judges' stay on-site [CO9]—to create their sample [CO12]. Having the judges verify the operation of the system and the contents of the samples would reduce the uncertainty in the solutions [CO4]: providing "proof that we're seeing CO_2 go into it, and we're seeing product come out, and we're going to know what that product is" [CO3].

Given these uncertainties, the formulation team decided that they would use the performance of the solvers in Phase 1 to set "realistic performance criteria" for Phase

2 [CO9]. Getting external input—before solvers actually solved the problem—would allow them to make better decisions on what solvers could do [CO3, CO9, CO2]; this would allow them to shape Phase 2 to be successful. And while the requests for information provided NASA with some feedback here, having them provide all that information in a formal challenge deliverable would be "the best way to obtain the necessary information" [CO9]. The delay between Phase 1 and 2 would also allow changes to be made without the paperwork—and potential embarrassment—of making big changes to the rules after they had been released [CO9]. The prize purse for this challenge was a total of \$1M [CO9]. Prizes for Phase 1 and Phase 2 would be \$50k and \$750k, respectively (up from \$500k initially) [CO4, CO5, CO9, CO19]. The bonus round in Phase 2 set aside \$100k of the \$750k prize for a separate award. Winning (or even participating) in Phase 1 was not required to participate in Phase 2.

B.2.3.2 The limits on the Footprint of the System

Initially, the SMEs imposed numerical limits on the system's footprint to fit the Mars implementation. Early drafts of the rules gave specific volume, power, and mass upper limits: if solutions exceeded these, they would not be valid [CO1]. Subsequent drafts removed or relaxed these numbers almost completely: stating that the system should fit within 25 ft^2 [CO6], and later 100 ft^2 [CO9]. In the end, the Executive Program Management Council (EPMC)—the challenge's final request for authority from NASA senior management to proceed—removed the limits on the system's footprint altogether [CO9].

Two reasons contributed to the decision not to specify any limits. First, judging the footprint fairly across different kinds of systems proved to be a difficult problem. Even excluding biological systems, there were many pathways—with as many processes—that solvers could create to perform the conversion [CO22]. These processes involved specific infrastructure, with their own space and power requirements, resulting in a wide range of potential systems. SMEs were concerned that consistently measuring the footprint of the varying solutions would be hard [CO22], and might not result in a fair judging process. At worst, this could have biased solvers towards certain processes—and thus, certain solutions—at too early a stage instead of focusing on glucose production [CO22].

Second, SMEs were afraid of imposing limits that would disqualify teams from getting close—but not quite achieving—the conversion goals. While size and power requirements would be front of mind for NASA's applications, SMEs did not want to dismiss potential solutions. In particular, they were concerned that these would hamper solvers so much that they would not complete the challenge, or not participate at all [CO22]. So by removing the explicit footprint limits, they could avoid these issues of fairness in judging and restricting solutions. Here's one SME describing their concern:

> [I]n doing the Centennial Challenge, you don't want to push it in such a way that it becomes impossible. That people say, "I could have done it, but it became so impossible that I couldn't do it. I could have gone 50% of what they're asking for." I don't want to eliminate that in the first step. [CO23]

Instead, reducing (or optimizing) the system's footprint would occur later. In deciding to remove the limits entirely, the attendees at the EPMC felt that Phase 1 should be easier for participants [CO2, CO22]—allowing them to focus on the conversion itself. Phase 1 would then "be more of a casting stage—spreading the net, seeing how many fish you can get" [CO2]. Simply having (non-optimized) estimates of what the footprint of such a system could be was valuable. Per one SME, "the main focus is: can [a participant] even do it. And if you do it, tell me what is the footprint" [CO23]. In that vein, the EPMC also suggested that the footprint limitations could be accommodated later, as "NASA will have time to work on the footprint limitation in the future when missions are defined" [CO9]. Here, the SMEs agreed with this change, adding "that creating glucose is the first priority of the Challenge, scaling a technology that can accomplish this can come second" [CO9].

Despite not having explicit limits, the SMEs stressed and incentivized a smaller footprint. While SMEs deferred the requirements to make the solutions fit into NASA aims, they felt that they needed to reinforce the space application of this technology [CO25]. As such, likely in line with the sentiment expressed in [CO23] above, the rules emphasized and incentivized small footprints. In both Phases, the rules informed potential solvers that "to increase the potential for use in space missions, scalable, low mass/power/volume systems are sought" [CO7, CO19]. In Phase 1, the system's footprint was an important factor under the scoring criteria of Applicability of Proposed System for Space Missions (itself 25% of the total score for Phase 1) [CO7]. And in Phase 2, a bonus competition related to the system's footprint was added [CO7, CO25]. Here, $100k of the prize purse would reward submissions' "effectiveness for future application in space missions" [CO19]. It would specifically grade solutions on making the solutions efficient in terms of power and conversion, the ease of scaling the operations, and the difficulties of operation [CO19]. Notably, the criteria did not capture the mass of the system—the formulation team could not come up with a way to fairly measure the equipment needed to produce the samples [CO25].

B.2.3.3 The Purity of the Sample to be Produced

The presence of contaminants in the sample A sample's glucose mass is not the only thing that determines its success as bacteria food. SMEs knew that certain compounds and intermediate products of the CO_2 to glucose conversion would be detrimental if they were present in the bacteria's food source. For example, even a sample with 90% glucose and 10% of certain other products would be "no good" [CO23]. Solutions that did not account for this would, ultimately, not be able to fulfill NASA's goal [CO2]. However, like scaling this technology to fit the Mars implementation, SMEs also deferred any requirements on the purity of the output.

Rules that would limit contaminants in solvers' solutions were hard to implement for a few reasons. First, measuring the composition of a sample was hard [CO3]. Quantifying all (potentially detrimental) products in the solvers' samples would be too complex a task for judges [CO22]. Another pathway that SMEs explored was the samples' compatibility as a food source [CO3]. This would be a (biological) test to ensure that the solvers' output would be compatible with the kinds of bacteria that SMEs would hope to feed [CO4]. However, this test would not be "even-handed" to all conversion approaches or candidate bacteria [CO23, CO9, CO3]. Second, it was possible to refine outputs to be compatible with different bacteria that SMEs would want to feed [CO2]. In this view, purification would be an extra step to the conversion, not an essential part of it [CO2]. Requiring that solvers tack this on would make the challenge too "large" [CO2] and add "complexity" [CO9]. Lastly, SMEs estimated that additional requirements to make solutions more compatible with its space application would make the challenge too expensive to solve [CO22].

In the end, SMEs decided to address the contaminant problem outside of the challenge context and did not add quantitative rules on contamination. [CO9]. The importance of demonstrating the conversion from CO_2 to glucose took precedent over how pure its sample could be [CO11, CO9]. Per one SME on the CCP team: "if we were able to just get the glucose molecule, regardless of whether it was compatible with [the test we had proposed], it would be considered a tremendous success" [CO2].

But the importance of contaminants was not forgotten. Instead of explicit rules governing the solutions, SMEs stressed their preference. They inserted statements in the rules that would—hopefully—focus the solvers on making something that would (eventually) be compatible with the Mars settlement goal [CO9]. For example, this line appeared in the rules for both Phase 1 and 2: "Likewise, the ability to make target compounds at high efficiency and specificity, and *with minimal contaminants and/or toxic by-products, is preferred*" [CO7, CO19, emphasis mine]. Additionally, SMEs felt that the solutions would still provide enough information to (somewhat) address the contaminant criterion at this stage. In judging the solutions, they would apply their expertise in the NASA context to identify which (kinds of) solutions would be most promising. One SME said it best:

> And sort of innately, we'll know– If we get a product stream and it contains a lot of toxic heavy metals in it, or it's highly acidic, or very, very salty, or fill in the blank. We'll go, "ok, in accordance to the rules, it's fine," but me as a NASA person will go, "we'll never be able to use this thing." So it's possible it still could be a winner in the challenge but not a viable candidate for our uses. And we're ok with that because it will still be progressing the field. [CO22]

Glucose versus other Carbon Products in the Sample The output of the conversion process was another area of uncertainty. Solvers' systems could create several intermediate products that, like acetate, could be food for bacteria [CO3, CO11]. These formed a ladder of increasingly higher carbon molecules (i.e., 2, 3, 4, 5, and 6-carbon products). Each were progressively more difficult to create from the CO_2 molecule, but also progressively more efficient as a food source: "not only is [a higher rung] more difficult, but it's also a better product" [CO2]. But this risked diluting the challenge's focus: solvers could chase high production rates of these intermediate products without actually producing any glucose. The SMEs had internal discussions about what it would mean for solvers to produce different combinations of these kinds of products. In these discussions, questions like the following would arise: "what if you got the glycerin [a 2-carbon compound], the lowest on there, if you have a pure amount of that, versus a very unpure amount of glucose? . . . So, which one do you like better?" [CO2].

In the end, the SMEs skewed the challenge's scoring towards the outcome they favored. The challenge as a whole would be pushing to "improve technology that is able to convert CO_2 into other molecules" [CO2], which the SMEs acknowledged would be an important technology to have in the future [CO3, CO2]. But to keep the focus on feeding bacteria efficiently, the SMEs decided that the intermediate products were valuable enough to score them too. SMEs weighted the scoring of the sample along those lines. Here, each carbon product would be weighted higher per their utility in feeding bacteria, with glucose receiving the highest weighting (the most important one) [CO7, CO19, CO5]. Thus, the rules would incentivize—but not mandate—the kinds of solutions that would best fulfill this function.

This presented a scenario where solvers could win without accomplishing the main goal. To counter this, SMEs tried to emphasize and incentivize solutions that addressed that goal. SMEs emphasized the glucose goal by positioning it at the top of the weighting factors and emphasizing it very strongly in the text of the rules [CO5, CO7, CO9] and other public descriptions of the challenge [CO12]. For example, using statements like "D-glucose being the most preferred" substance [CO9, CO7], or stating they were "looking to push the envelope, so to speak, to move [CO_2 conversion] towards [these] sugars" [CO12].

B.2.3.4 The Production Rate and Sample Size

Both the sample size and the time allotted to produce it fluctuated. At first, they limited the system's operation time to 4 hours [CO1, CO5] and asked for specific amounts of product to analyze in grams. One of the last drafts of the rules went up to 4 grams in 4 hours. This number was based on amounts needed to perform three analyses in a lab accurately—smaller amounts were at risk of running into physical detection limits [CO9]. But at the same time, there was a concern about requiring a certain sample size and having solvers undershoot that amount. The EPMC specifically stated their "concern that 4 grams in 4 hours might be too much" [CO9]. Other concerns raised also included shifting the focus of the solver from producing some glucose to producing a lot of lesser product: "What if they produced just 1 gram of glucose (which is ultimately what we want)? They would not meet success requirements the way the rules are written now" [CO9].

Ultimately, SMEs decided to remove production rate/sample size limits. Initially, the uncertainty of estimating how these solvers would perform pushed the decision on what the minimum production rate would be until after Phase 1 [CO9]. Contrary to earlier versions of the rules, Phase 1 did not include how much product the challenge required [CO7]. Instead, they gave solvers a production window and stated that their samples would need to be "enough" to be analyzed by specific tests at NASA Ames [CO12, see also CO9, CO19]. Thus, the rules did not explicitly require solvers to scale their systems to a determined output. Instead, solvers would be allowed to interpret that requirement based on their expertise and available infrastructure. Their samples would be scored by the mass fractions of the desired products in the sample [CO19]. Note here that even with the Phase 1 results received, SMEs decided not to require a specific sample size for Phase 2 [CO19].

Despite removing these limits, SMEs communicated the importance of scaling through the points. They incentivized the design of the solutions to be scalable by scoring these kinds of solutions more heavily [CO7, CO19]. In phase 1, this was part of the Applicability of Proposed System for Space Missions category, with 25% of the score [CO7]. In Phase 2, this criteria formed 30% of the bonus round's score [CO19].

B.2.3.5 Excluding Biological Solutions

In contrast to decisions on the other focus areas, NASA SMEs made a definitive choice on what conversion approaches solvers should (not) use in their solutions. Specifically, solvers were to avoid biological approaches to convert CO_2 to glucose. There were two reasons why: the relevance in addressing NASA's need and difficulties judging the solutions. The former was about the technology family that the SMEs wanted to develop: SMEs wanted to "push past what biology can do and set bar high enough so it's a stretch for people" [CO11]. Because "biomass [was] not going to solve the problem" [CO11] of providing NASA with an efficient method of feeding bacteria on Mars [CO12], the goal of the challenge was to find a better pathway, not just any pathway [CO3, CO24]. The latter was about the judging of the biological solutions. SMEs were concerned that this was an area where solutions might seem operational, but the underlying problem had not been solved. Here's how one SME described their concern: "there are ways to skirt the system to make it seem like you're doing it and it's not going to work" [CO3]. So, the rules [CO5, CO7] and presentations about the challenge [CO12] made it very clear—from the start—what the challenge was hoping to accomplish.

This exclusion would (mostly) extend to products that could be used in solvers' reactors derived from plants or bacteria. SMEs clarified the intent of the rules after the challenge was posted. As with other CCP challenges, the solvers would submit questions to the formulation team. While some solvers asked for—neutral—clarifications of the rules, some asked for the SMEs' blessing on a proposed approach. This was the case here too. Per one of the SMEs, some solvers were trying to be "cute" [CO23]. While they knew that biological approaches were not allowed, they asked whether compounds derived from organisms would be allowed instead. The problem here is the supply chain to the Mars settlement: they would have no way—other than biological processes—to replace these compounds once they ran out. So, they were not considered valid entries for the challenge [CO13]. However, the SMEs decided not to clarify this as an update to the Phase 1 or Phase 2 rules [CO19, CO9]. One SME stated that he "did not want to throw away" solutions that had some biological processes in them, despite the problems above [CO24].

B.3 The Outcomes of the Challenge

B.3.1 Feedback from (Potential) Solvers before the Solution Submission

The SMEs received strong pushback from solvers interested in pursuing the biology approach [CO23]. SMEs received this feedback in the requests for information that preceded the challenge's launch and as informal questions submitted by (potential) solvers [CO4, CO13]. Pursuing the conversion using only non-biological means was the exception, not the norm; several teams (with expertise in biological systems) tried to push the rules towards these systems anyway [CO4]. Imagining themselves as a solver, the lead SME acknowledged that that constraint was counterproductive and a "thorn in their side" [CO24]. However, SMEs did not want this challenge to be "swamped" with bio-solutions that could likely outperform others just because they are more mature or developed [CO24]. So, they stuck to their exclusion. But this explanation did not seem to appease all interested teams. One SME said that they told solvers, "'sorry that's not going to work,' and they weren't happy about it" [CO10].

This pushback worried the SMEs. It signaled to the SMEs that those following the challenge also realized that it would be difficult, especially since the bio-pathway had been closed off. Thus, they were worried that the challenge would not see healthy participation. Per a SME: "we're taking a bit of a chance. We're going to restrict our participant base a bit to focus on it more diligently. And we're crossing fingers that we get the response we need to host a healthy challenge" [CO3]

B.3.2 SMEs' Reflections on the Solutions

Despite their initial apprehension going into the challenge, the SMEs were generally pleased with the solutions' quality and quantity. I explain both below.

B.3.2.1 Quality

Teams delivered successful solutions in both Phase 1 and Phase 2, taking home the prizes in both. In Phase 1, the SMEs estimated that at least the majority of the submissions were good, with some even being excellent: a "third were excellent, a third were good to ok, and a third were not very applicable" [CO22]. Here, the top five teams took home \$50k [CO20]. In Phase 2, three teams successfully demonstrated their conversion system, taking home equal shares in the \$650k prize purse [CO21]. Additionally, these same teams won the Phase 2 bonus round [CO21]: one industry team won the \$50k top prize, and the other two took home \$25k. As a testament to the quality of the highest performing solutions (in Phase 1), one SME remarked that the judges were happy to reward teams for their performance, not just because they followed the rules [CO22].

How did the judges judge their confidence in the solutions? While the Phase 2 rules did contain some quantitative ways of calculating the solvers' final score, a lot of the scoring throughout this challenge was more qualitative. Moreover, Phase 1's criteria did not include a quantitative output at all. As such, success—particularly in Phase 1—meant speaking the same language and showing that you knew the material well [CO3]. SMEs wanted solvers to show that they had been thinking about this problem for a long time, not "like someone had an idea in the shower and they [wrote] it down" [CO22]. They expected solvers to show that they had gone through the appropriate literature out there and ensure that they did not propose something that had (partly) already been tried and failed [CO22]. It even came down to the references that the solvers would use. Per an SME, they were looking for:

> "... markings of a clear understanding of the problem, providing background to their solution. Where it's being derived from. If they can provide a logical argument as to why this would be a good way to go after this problem. And then there is understanding their chemistry. Or whatever field it is that they are using to solve the problem, including references." [CO22]

SMEs thought “the solutions were hopeful and promising of getting somewhere” [CO22]. They acknowledged that these solutions made some headway into the CO_2 to glucose conversion problem [CO20, CO21, CO22]. And they found this work valuable even with the limited ability to match the rules to NASA’s requirements [CO22]. The solutions presented some new conversion pathways: some combined known chemical processes in new ways, others performed known conversions in new ways (with the latter being more valuable) [CO22]. At the same time, however, SMEs remarked that they did not see anything surprisingly novel in the solutions. They did not expect to see a “miracle cure” and did not see one either [CO22]. Instead, solutions delivered “middle of the road, good solid progress” on non-biological conversion systems [CO22]. Here’s how one SME summarized his view on the advancements made by the solutions:

> [There] wasn’t anything that we went “Wow! Oh my goodness, this is out of this world.” It’s chemical engineering. The solution space is fairly well-defined whether or not you’re innovative in that area. A lot of the advances right now are just iterative improvements on old systems. Finding a slightly better catalyst, or one that lasts longer, or a lower temperature to operate it, or finding ways to make less waste products. . . . There’s mild to medium innovation here [in this challenge]. And it’s good. It will advance– It will push this field forward. Everybody typically hopes for a miracle solution to things, right? And physics usually doesn’t allow it. [CO22]

The SMEs’ strategies to balance their aims influenced solvers and their solutions. Most solvers explored conversion methods that relied fully on non-biological approaches, and some even pursued versions of their systems that could work in NASA’s context. In Phase 1, for example, some solvers explicitly described how their solutions addressed NASA’s aims by, e.g., being able to regenerate their catalysts [CO14] or limiting their consumables to exclusively Mars in situ resources [CO14, CO18]. Additionally, three teams won prize money for accommodating the bonus objectives in Phase 2 of “efficiency, scalability, and reliability” [CO19].

While the challenge generally made progress on conversion systems, the biological exclusion rule was still an issue for some solvers. According to the SMEs, only one solver pivoted from the initial path of something that would not work to something that would [CO10]. The ones that could not—or did not want to–pivot submitted non-compliant solutions anyway [CO24]. In the same vein, SMEs remarked how it was the academic teams that were less likely to venture outside of their wheelhouse of knowledge; in contrast, industry teams were "scrappy and [tried] to pull in what they need when they need it" [CO22].

B.3.2.2 Quantity

Overall, SMEs "got a lot more applications than [they] thought [they] were going to get, which was excellent" [CO10]. Over a thousand teams—1415 in total—showed an interest in participating; hundreds of teams—210 in total—completed the challenge's preregistration form [CO34]. In the end, 24 different teams participate across both phases [CO34]. In Phase 1, 20 teams submitted solutions. Of those, CCP classified five teams as academic teams (e.g., PI-led research groups), seven as industry teams (e.g., start-ups), and eight as other (e.g., unaffiliated research teams or hobbyists) [CO34]. In Phase 2, the number of teams dropped to eight. Of those, CCP classified two as academic teams, three as industry teams, and three as other [CO34]. Only four teams, all of whom were winners in Phase 1, participated in both phases [CO34].

The SMEs were also surprised about the number of compliant solutions they received. The pushback from teams working on biological systems painted a different picture than the challenge's outcomes [CO10]. One member of the formulation team even remarked that the challenge might not have been as hard as the SMEs envisioned it would be for external solvers [CO26]. Here is how one SME described his view of the number of "good" solutions (in Phase 1):

> Initially, we were quite worried that enough viable ideas were actually going to be submitted, and we got plenty, and we were quite happy with that. The five that were selected [in Phase 1]— There were some that were better than others, but they were all above the bar of what we were thinking, and we were pleasantly surprised . . . I think you can say [I'm] surprised from the perspective

> of “we didn’t expect so many people to apply and so many good applications to be submitted as well. [CO22]

Lastly, the challenge attracted teams that were both known and unknown to the SMEs. Because of their knowledge of the field, SMEs expected certain individuals and their institutions to participate in the challenge, even reaching out to several companies who would potentially be interested [CO2]. This had a lot to do with their capabilities [CO23, CO2]. SMEs expected some teams to participate, and they did, but others did not [CO22]. SMEs also expected that the challenge could attract “an entirely new cadre” of individuals and teams [CO23, see also CO3], in particular, those “who typically don’t participate in NASA calls” [CO22]. And they did as well. SMEs described several teams—mainly start-ups—who “came out of the blue” and participated in the challenge [CO22]. While most teams had strong backgrounds in CO_2 conversion technology [CO10], several solvers did not have previous experience in the aerospace industry [CO28, CO29, CO30, CO31]. One of these non-aerospace solvers expressed that the challenge helped them realize that “NASA will need serious chemistry research for Mars exploration tech” [CO30]. This team even went so far as to explicitly say that they wanted to pivot their business to become a supplier to the aerospace industry (including NASA) based on the work in the CO_2 to glucose challenge [CO30].

References

Table B.1: References used in the “Formulating the CO_2 to Glucose Challenge" Case Narrative

Reference	Date created	Description
CO1	Sep 11 2017	First draft of CO_2-to-Glucose RFI
CO_2	Apr 18 2018	Interview with SME CC8 about the start of CO_2
CO3	May 3 2018	Interview with SME CC11 about the start of CO_2
CO4	Oct 27 2017	Centennial Challenges Program presentation to STMD
CO5	Apr 4 2018	Second draft of CO_2-to-Glucose RFI (with comments)

CO6	Apr 4 2018	Released CO_2-to-Glucose RFI
CO7	Aug 16 2018	Final Phase 1 rules
CO8	Aug 16 2018	CO_2-to-Glucose FAQ V1
CO9	Aug 16 2018	Internal discussion and resolutions of issues brought up by the EPMC
CO10	Oct 10 2019	Interview with SME CC11 after phase 1
CO11	Mar 14 2018	Kickoff meeting CCP and Common Pool
CO12	Feb 28 2020	Phase 2 webinar
CO13	Oct 2 2018	CO_2-to-Glucose FAQ V2
CO14	May 16 2019	Summary of winner's solution (Phase 1)
CO15	May 16 2019	Summary of winner's solution (Phase 1)
CO16	May 16 2019	Summary of winner's solution (Phase 1)
CO17	May 16 2019	Summary of winner's solution (Phase 1)
CO18	May 16 2019	Summary of winner's solution (Phase 1)
CO19	Sep 16 2019	Final Phase 2 rules
CO20	May 16 2019	Press release detailing Phase 1 winners
CO21	Aug 24 2021	Press release detailing Phase 2 winners
CO22	Oct 18 2019	Interview with CC11 on the results of Phase 1 and expectations for Phase 2
CO23	Apr 1 2020	Interview with SME CC28 on the start and formulation of the challenge
CO24	Feb 26 2021	Informal conversation with CC26 and CC11 on Phase 2 formulation
CO25	Aug 26 2020	Informal conversation with CC26 on CO_2 challenge formulation
CO26	Jun 5 2019	Informal conversation with CC26 on Phase 1
CO27	Oct 8 2020	Interview with solver CO1U1 on participation in Phase 1
CO28	Oct 2 2020	Interview with solver CO2SB1 on participation in Phase 1
CO29	Oct 2 2020	Interview with solver CO3U1 on participation in Phase 1
CO30	Oct 1 2020	Interview with solver CO4SB1 on participation in Phase 1
CO31	Oct 24 2020	Interview with solver CO5SB1 on participation in Phase 1 (written questions)
CO32	Jul 3 2019	Feedback from solver CO5SB1 based on CCP questionnaire
CO33	Jul 29 2020	Meeting with CC26 on challenge formulation
CO34	n/a	CCP list of all CO_2-to-Glucose participants and winners

Appendix C—Formulating the 3D Printed Habitat Challenge

This appendix summarizes how NASA's Centennial Challenges Program, along with NASA's additive construction subject matter experts and experts from outside the space industry, created and formulated the 3D Printed Habitat Challenge (3DPH). It highlights the important decisions that shaped the problem that participants would solve when they competed.

The challenge presented a series of relevant problems to a broad audience, with multi-million dollar prizes for the best solutions. Its aim was to incentivize non-traditional, (and even) non-aerospace entities to contribute to a NASA problem, in the hopes that their solutions would advance the state of the art of additive construction. By all accounts, both inside and outside NASA, the 3DPH challenge was a huge success. The challenge launched in 2015 and ended in 2020.

C.1 Introduction

NASA plans to land astronauts on Mars but faces steep mission costs to do so. Putting objects in orbit is expensive: one additional kilogram of launch mass adds thousands, if not millions, of dollars to the overall mission [3D180]. The astronaut crew will need thousands of kilograms of infrastructure and consumables to stay alive; this makes the cost problem many, many times worse [3D190]. To address this issue, SMEs across the agency investigate how resources on Mars could create the needed products instead of transporting them from Earth [3D180, 3D115, 3D191].

One such approach is additive construction using resources in-situ [3D65]. This construction method draws on additive manufacturing and uses a robotic printer to lay down successive strips of material. These strips fuse to form the desired object.

Additive construction could reduce *both* the construction costs and risks. First, it uses materials found on the planet's surface to construct things like landing pads, roads, and even habitats [3D180, 3D130, 3D190, P23]. This way, NASA could avoid launching "thousands of tons" of construction material and save many millions of dollars [3D180, see also 3D190, 3D120]. Second, it reduces the risks of constructing the needed infrastructure. The crew will need adequate, large-scale housing for their monthslong stays on the planet. But, at current levels of shielding, the radiation levels on Mars make it extremely dangerous for the crew to construct this infrastructure when they arrive [3D226]. Instead, NASA envisions robots performing these tasks remotely, with a high degree of automation. Additionally, the independence promised by this technology will reduce the risks of accidents during the construction process [P23, 3D120, 3D190].

To help address this gap, NASA's CCP launched a series of public-facing technology competitions to spur the development of these technologies. NASA's 3DPH ran between 2015 and 2019, launching four prize competitions. I summarize the 3DPH Challenge below, focusing on the decisions that shaped the technology requirements participants faced. Specifically, how the 3DPH rules team decided what problems participants would solve.

This document proceeds as follows: First, I explain the origins of the Additive Construction with Mobile Emplacement (ACME) Challenge and the relevant context at NASA at the time. Then, I provide an overview of the 3DPH Challenge: its structure and timeline. Finally, I describe each competition: its aims, what participants would focus on, how the most important rules were decided, NASA SMEs' reflections on the outcomes, and any lessons that would carry forward.

C.2 A Challenge on Additive Construction

C.2.1 Why Launch a Challenge?

The push for a challenge stemmed from the Obama Administration—it would be a catalyst for technology development and nontraditional input. The Administration recognized additive manufacturing generally as a strategic priority for the US and wanted to encourage a broad exploration of this capability [3D1]. The administration also acknowledged that "knowledge is widely dispersed in society" and that innovation tools like challenges could tap into new and existing sources of expertise, benefiting the agency and the country [3D205, see also 3D206]. In this vein, it directed NASA and the U.S. Department of Energy (DOE) to spur innovation in robotics and additive manufacturing in 2013 [3D1, 3D30, P18]. Specifically, they directed NASA to draw on their prize authority[1] to spotlight specific research and development challenges that overlap with the agency's priorities [3D1].

NASA would decide what application of additive manufacturing they would challenge. NASA's CCP consulted with SMEs for input on applications of additive manufacturing that would make sense to space and non-space contexts [3D11, CCP7]. Here, CCP reached out broadly both inside and outside the agency. They approached contacts in industry (e.g., Boeing and GE Aviation), government (e.g., United States Agency for International Development (USAID) and USACE), and additive manufacturing teams at MSFC and KSC [3D103, CCP7, 3D11]. In the end, the external input helped CCP settle on additive construction of planetary habitats [3D11].

The CCP reasoned that a challenge on additive construction in the space context would fulfill the administration's mandate: support ongoing work at NASA centers and attract the input of (non-space) non-traditional contributors. While planetary additive construction was a niche topic at NASA, it had the potential to make a big

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[1] In 2005, 51 U.S.C. §20144: Prize authority granted NASA legislative authority to use appropriated funds to conduct public prize competitions. NASA established the Centennial Challenges Program to award prizes for technical achievements that aligned with its aims.

impact on long-duration surface exploration. By shining a light on it, CCP hoped that others would see this potential and help move its development along. Per the CCP Program Manager: "[the 3DPH Challenge] is the way that we, as an agency, reach out to all of you, our nation, to come and help us put a little piece of our puzzle in the journey to Mars" [3D122]. Additionally, building shelters quickly and efficiently was an area of active work in disaster relief and military contexts [3D11, 3D35, 3D33]. Much like printing infrastructure in space, these projects were concerned with minimizing the human effort required for the required structures and utilizing local resources and waste to the greatest extent possible. Being aware of the work of external teams on this topic, the challenge team hoped to draw these teams into the challenge as well.

C.2.2 Supporting Ongoing Work at NASA

C.2.2.1 Existing Additive Construction Programs at NASA

Research into additive construction for planetary surfaces had been ongoing at NASA. Specifically, teams at both NASA's Marshall Space Flight Center (MSFC) and NASA's Kennedy Space Center (KSC) pursued related technologies for several years [3D35, 3D160, 3D163]. These then collaborated on the ACME project, alongside several external partners like the USACE and Caterpillar [3D33, 3D34, 3D35]. The project brought space and non-space SMEs together to explore the overlap between printing temporary housing for the U.S. Army and the planetary infrastructure required by NASA [3D28], emphasizing developing the technology for large-scale printing [P17]. It also gave SMEs at KSC an opportunity to pursue the development of polymer concrete feedstocks[2]: these used plastics to bind, extrude, and layer regolith into the desired shapes[3D130]. In addition to having desirable material properties for applications in space (see C.5.2.2 for a summary), they could also support sustainability efforts here on Earth [3D94, 3D185].

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[2] Analogous to a printer's ink.

Notably, the ACME collaboration ran (almost) parallel with the 3DPH Challenge, with their expertise contributing to its formulation. The ACME project had only recently demonstrated large-scale 3D printing when the formulation of the 3DPH challenge started [3D65]. The ACME project and the 3DPH challenge had similar goals: large-scale automated printing of infrastructure with readily available materials [3D33]. Though they had not initiated the challenge, NASA SMEs on the ACME project knew that their expertise would, nevertheless, be required to formulate it [3D89, 3D11, 3D185]. They took this opportunity to shape the challenge towards their ends: once on the challenge's formulation team, these SMEs would ensure that it complemented their work. Below, an additive construction SME described how they saw the role of the 3DPH Challenge and CCP challenges more generally. Though Blake[3] joined the 3DPH Challenge's formulation team after it was already underway, they understood how closely related the challenge was to their work.

> Ademir: In your mind, where do challenges fit in [to your work]?
>
> Blake: A very complementary role to what we're doing. ... In [the 3DPH Challenge's] case, it was so tightly interwoven with all the stuff we were doing in terms of the ACME system that we were building that there was no way that Finley[4] [an MSFC SME] and I weren't going to get pulled into the challenge. I was always monitoring it. [3D89]

C.2.2.2 Pushing solvers to explore useful solutions

The KSC and MSFC teams wanted to ensure that the challenge would extend their work. As such, these SMEs actively shaped the challenge to make it more likely that its outcomes would support their technical goals. First, based on their knowledge, SMEs would select technology areas that were particularly underdeveloped or highly uncertain and might benefit from external input. In particular, they would focus solvers on specific parts of the planetary additive construction problem, incorporating

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[3] A pseudonym.

[4] A pseudonym.

NASA's constraints and interests. Jude[5], an SME that assisted the formulation team, put it as follows: "we knew what troubles we were having, and we focused the competition to do something about those troubles" [3D185].

Second, SMEs worked hard to translate their knowledge of the Martian environment and NASA-specific interfaces into (reasonable) boundary conditions for the challenge. This way, the problems would—to a certain degree—reflect the conditions that they understood and were working towards. For example, Blake described how the SMEs wanted to impose their (current) knowledge on the challenge's rules. Specifically, what kinds of materials would be more favorable to create a feedstock for Mars: "We were getting our needs put into the system there. We were saying, 'we need to make sure that the materials [the solvers] use are as relevant to planetary materials as possible'" [3D89].

The SMEs' general approach to formulating the challenge was top-down. Having worked on this and related problems, SMEs were very familiar with the context. Their knowledge included the problem's important factors, for example, Mars' planetary conditions, materials available once the crew landed, current additive manufacturing capabilities, and more [3D36, 3D103, 3D80, 3D81]. To formulate the different phases and their competitions, SMEs would, first, think about the performance or development they wanted to incentivize. Then, they would figure out what assessments or evaluations were needed to ensure that solvers met that goal [3D93, 3D105]. SMEs "started at the macro and then went down more into the micro" in their formulation process, per Harper[6], one of the non-NASA members of the formulation team [3D105]. Harper went on by saying that at the "micro," the team would "[bring] reality in a little bit again" [3D105]. Specifically, questioning how non-NASA solvers could (realistically) meet the challenge, how they could practically score the incoming submissions, and what boundary conditions needed to be considered [3D105].

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[5] A pseudonym.

[6] A pseudonym.

SMEs on the formulation team wanted to align the 3DPH problems to their internal ones *and* push solvers to explore new solutions. SMEs did not see themselves as (overly) prescribing what solutions to their problem would look like. Instead, they described how they were trying to balance a completely feasible problem and pushing the boundaries. As Ash[7], an SME on the formulation team, put it, "if it's completely feasible, then there's no point in having the competition" [3D103]. While SMEs understood key parts of the problem, there were many design decisions, trades, and practical issues to overcome [3D82, 3D89]. Here, solvers would explore that tradespace and develop solutions built on their expertise and knowledge. For example, Jude described how they viewed the balance between the leeway given to the solvers and boundaries on their solutions:

> [W]e didn't want to overconstrain the rules and prescribe a solution. We wanted to allow the teams to innovate and do things that we hadn't thought of. But we knew the basic building blocks that they needed to work within. We knew the basic constraints. ... we knew we wanted to minimize launch mass, we wanted to use as much ISRU as possible, and we knew that there were things that we knew were getting close to be able to doing, but not quite able to do yet. So, we think they're possible, but we don't exactly know how to do it. So, let's choose things that they have to do, that are in that direction, so that we can actually learn from these guys too. [3D185]

C.2.2.3 Priority areas of additive construction

The SMEs ensured that this challenge would address key areas of additive construction. They focused heavily on developing new feedstock materials, ensuring the autonomous operation of the printer, and creating the robotic architecture required for large-scale structures [3D94, 3D11, 3D89]. The feedstock is foundational to this process: the printer prints with in-situ materials, dictating its design and capabilities. Autonomous operations are required on Mars to protect astronauts from dangers associated with construction—ideally, the habitats will be complete before they arrive. Lastly, habitats are only useful for the crew when printed to scale—SMEs wanted

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[7] A pseudonym.

printer systems to be designed and built with this in mind.

To make progress on the capability of additive construction, one would have to consider these priorities together. Per Ash, design decisions in one area impact the others: “It’s a Venn diagram. They’re all equally important, they all have their own challenges. They’re all enabling. If you’re missing any one of those— It’s a three-legged stool” [3D94].

This interdependence increases the complexity of the challenge. Specifically, the printing system also limits what kinds of geometry—and thus types of infrastructure—can be printed. Blake stated this succinctly: “You can’t build a printer that’s open-ended and can build any geometry” [3D89, see also 3D226]. As such, the habitat design would have to incorporate all three areas to reasonably model a deployment to Mars. So, the architectural habitat designs and printing system designs became an additional focus area in this challenge[8] [3D11].

C.2.3 Drawing External Contributors

The 3DPH Challenge connected NASA SMEs with a range of people and organizations, both inside and outside the space industry. These contributed to formulating and solving the problem. CCP’s long history of running challenges, with several high-profile successes, meant this approach was a known way to involve non-traditional entities [P13]. SMEs relished the idea of working with smaller, non-traditional players in their day job. They were, for example, “so much more nimble and flexible and can just change on a dime,” compared to the larger aerospace multinationals that they would normally do business with [3D185]. Despite lacking resources, those entities “have great intellectual capital and have great ambitions,” as Jude described [3D185]. SMEs appreciated that challenges would provide a (new) avenue for external collaboration. Quinn[9], an SME on the formulation team, summarized how they saw

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[8] There were other reasons for pursuing an architectural focus area, and these are explained in C.4.1 and C.6.3.1.

[9] A pseudonym.

the utility of challenges in enabling their work:

> [Challenges] have been good at finding innovation in unexpected places. Not necessarily government research institutions or academia, but really represent a great way to bring in garage maker innovators, who probably aren't out there applying for government contracts or even thinking about government work in any capacity. So, it's really an opportunity to bring them into NASA, you know, and let them help us with technology development. I think that's a really unique feature of CCP, that it's really that public-facing opportunity in a way that our traditional contractual mechanisms aren't sometimes. [3D36]

Entities outside of NASA, and even outside the space industry, contributed significantly to the problem NASA was facing. All competitions saw a mix of academics, companies, and hobbyists participate. In fact, SMEs were very open to input from different industries–they wagered that they would have different competencies and ideas relevant to the problem [P13, 3D104]. And they expected the challenge to facilitate that. As Ash described, the 3DPH Challenge team wrote the rules to overlap terrestrial and space industries, so "the competitors could still compete and meet their own goals while meeting NASA's goals" [3D103]. Fran[10], an SME who observed the 3DPH Challenge, described how they believed challenges could provide that avenue to connect with entities outside the space industry:

> We [at NASA] fight constantly to get outside the known group of people and companies that we deal with. How do we get outside the aerospace industry? How do we get the Bechtels, and the Caterpillars, and the mining companies involved when they don't go to the conferences we go to? They don't necessarily look at the government solicitations that are put out that we put out. A challenge breaks that paradigm somewhat. [3D100]

While non-space entities participated as solvers, some also contributed to the formulation of the challenge. The 3DPH Challenge team recruited external (non-space) advisors on the formulation team. This was a big deal for the challenge. Across all phases, they received input—or sponsorship—from SMEs in non-space industries, including international development, architecture, construction, and the

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[10] A pseudonym.

military [3D105, 3D107, 3D108, 3D122, CCP49]. These external SMEs would describe the capabilities of their industries to their NASA counterparts—what the state of the art and the barriers to entry were—and helped write the rules along these lines. It also became an opportunity to (re)connect or expand their connections to public or private sector organizations and use their knowledge [3D31, 3D94, LE1, LE3, P19]. Finally, the external SMEs also helped market the challenge to their own external communities, judge the solutions, and importantly, write the rules. One of the contributors, Caterpillar, even provided access to a facility to host the challenge's finals and equipment to test solvers' solutions.

Of course, solvers would also benefit from their participation in the challenge. Winning the large monetary prize was an important draw for many participants, but not the only one. Several teams wanted to use the challenge develop—and demonstrate—a technology, or to build a revenue stream in their company [3D196, 3D202, 3D210]. Others wanted to use the challenge to make a name for themselves through the challenge's visibility [3D198, 3D207]. Relatedly, challenge organizers would not only provide access to the (NASA and non-NASA) SMEs on additive construction, they would also introduce teams to potential sources of funding and even other competitors in the challenge [3D227].

C.3 The Structure of the 3DPH Challenge

The 3DPH Challenge would offer upwards of \$2.5M to address the additive construction technology gaps it highlighted. Solvers would address these gaps–and win parts of this pot–across different phases of the challenge.

Across three phases, the 3DPH Challenge held four independent competitions: the Design Competition, the Structural Member Competition, the Virtual Construction Competition, and the Construction Competition. Each competition focused on different technical areas of interest to the NASA SMEs, with their own cohesive rule set, prizes, and judges [3D17, 3D31, 3D23, 3D76, 3D108]. Each competition also included (one or more) levels—nine in total. And each level had various performance goals, and the challenge team awarded a prize for the best performance(s). Figure C.1 illustrates this structure below: each phase is pictured in light grey, their respective competitions in dark grey, and in turn, the different levels per competition are in black.

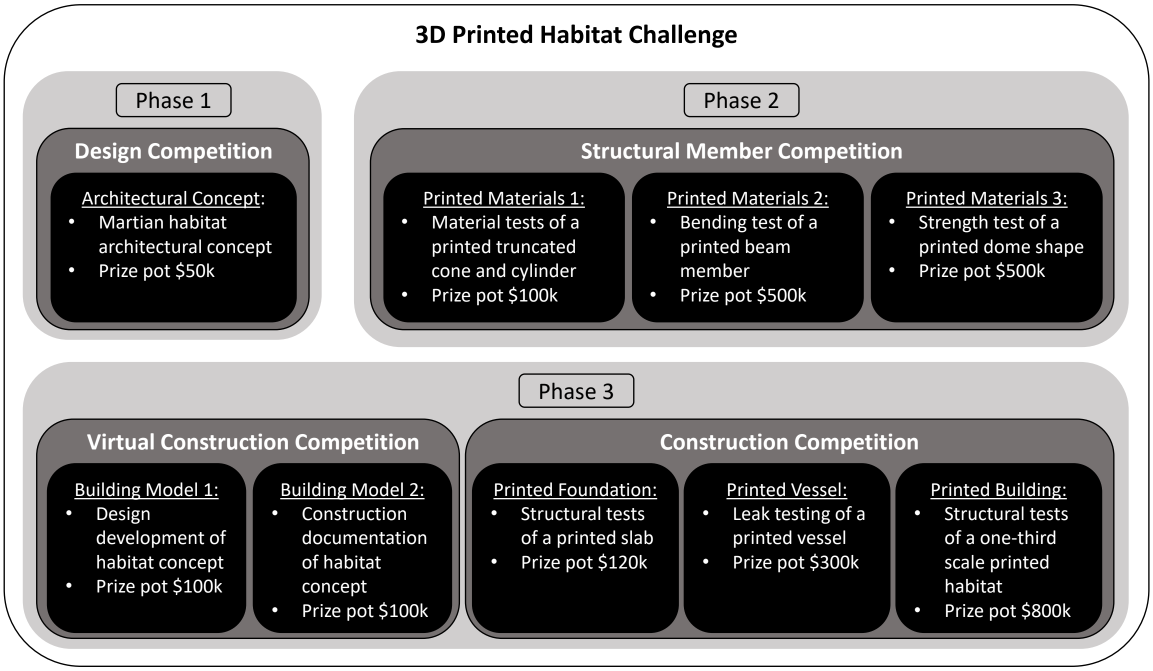

Figure C.1: 3DPH Challenge Structure

SMEs did not decide the challenge's exact structure when they first conceived the 3DPH Challenge. Early on, the formulation team only had a high-level picture of what the challenge would look like: NASA's technology gaps and potential challenge goals. The team also believed that the challenge's phases "should gain in difficulty," serving an onramp for participants that had not already been working in the space industry [3D227]. Further details would solidify as the challenge progressed [3D103], resulting in the above phases. SMEs used this flexibility to learn from preceding phases and course-correct the challenge (and the rules) when necessary. Figure C.2 summarizes when the formulation took place. It also emphasizes that formulation occurred across the challenge, with one major revision of the focus of the competition. As Ash described:

> Each time we started a new phase, there was a big debate on what should the new phase be. The phases were not really defined all the way in advance. ... It's probably good that we didn't try to do the rules for Phase 3 before learning the lessons in Phase 1 and 2. So, [for] each phase, it's important not to get ahead of yourself. [3D103]

The sections below explain the evolution of the challenge's structure, focusing on how the challenge team formulated each competition.

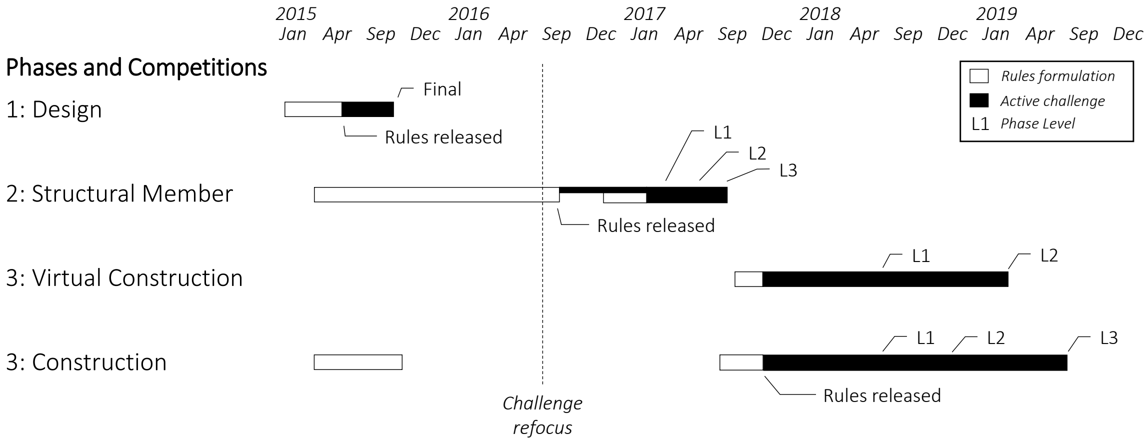

Figure C.2: Timeline of the 3DPH Challenge

C.4 Phase 1: The Design Competition

The 3DPH Challenge's first phase consisted of the Design Competition. It challenged solvers to create architectural concepts for habitats on Mars. It was the shortest of all competitions, running from March 2015 to September of the same year. The Design Competition offered only one prize award, with a total prize pot of $50k. See Figure C.3 below for a visual summary.

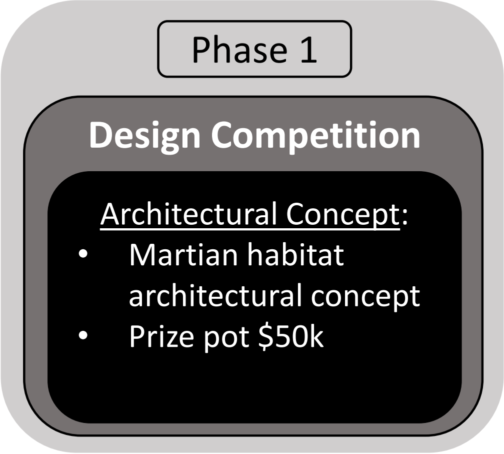

Figure C.3: Summary of Phase 1 of the 3DPH Challenge

C.4.1 Establishing the Design Competition

C.4.1.1 The Focus of Phase 1

Additive construction is a new construction method, and its capabilities have barely been explored [3D3]. Like additive manufacturing, it lays down individual layers of material that combine to form a single solid shape. This method can enable several advantages over others, for example, automated and remote construction, quick and efficient building, and designs of structures and buildings that have either not been possible before or were more difficult to accomplish through other means [3D13, 3D65, 3D180].

In this vein, the Design Competition intended to explore the range of habitat designs that would be possible using additive construction [3D2, 3D17, 3D31, 3D69, 3D72]. The printer's design significantly influences what geometries it can print [3D160]; to obtain the widest range of designs, one would need to (allow others to) explore both simultaneously. The formulation team wanted to encourage the exploration of both, resulting in habitat designs that would suit NASA's aims for a Mars settlement [3D4, 3D117]—nominally, a structure to house four astronauts for one year [3D17]. Speaking to potential participants at Maker Faire 2015, the CCP

Program Manager at the time described what kinds of solutions they wanted to see:

> I want you to think, "how can I use 3D printing, so I don't print a cube house with a slanted roof?" There's got to be more unique opportunities and more unique designs that can be taken advantage of because of doing 3D printing. [3D118]

C.4.1.2 Logistical considerations

The Design Competition, at least partially, served as a stop-gap for NASA SMEs to plan the subsequent challenge phases. During the early challenge formulation meetings, the team realized that they needed more time to craft good rules—especially for phases where they would ask solvers to demonstrate their solutions [3D30, 10CCP, 15CCP]. Specifically, SMEs wanted to dig into both the "material that would be used" and "the system to build the habitat," per Riley[11], a CCP team member that contributed to the early formulation of the 3DPH Challenge [3D11]. But the team was also under pressure to release something soon: there had been little progress on the Obama Administration initiative that had driven the formation of the challenge. Needing a quick win, the team figured that a design challenge could give them the delay they needed [3D11, 3D30]. So, the formulation team decided to get the approval for—and launch—the Design Challenge first[12] and return to the drawing board for the subsequent, bigger phases [15CCP].

C.4.2 Formulating the Design Competition's Problem

The formulation team drew heavily on the architecture domain because of the challenge's focus on building design. Here, they relied on the architectural experience of some of its members to shape the rules [3D4, 3D7, 3D8], and later, on architects to judge the competition [3D72, 3D80]. Ash summarized the formulation process for the Design Challenge as follows:

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[11] A pseudonym.

[12] The 3DPH Challenge partnered with America Makes to provide logistical support in administering this competition [3D72, P5, P19, 17CCP].

> In Phase 1, the goal was architectural design. So, we had architects on the team, and we asked them, "in your profession, what do you desire?" And if you go to the rules for Phase 1, you'll see the list of architectural criteria. And the rules were basically structured around those criteria. [3D103]

These criteria shaped both the form of their solutions and the problem that participants would solve [3D3, 3D4]. For the former, the challenge would require a conceptual design (in documents and presentations) and its tabletop model—common deliverables for architecture competitions. By selecting these, the formulation team also tried to keep the costs of participating low[13], with early notes stating an estimated expenditure of no more than \$10k [3D3]. Solvers would first submit their concept illustrations and descriptions for initial judging. If successful in these early rounds, the challenge would invite solvers to 3D print a small mockup of their habitat. As assessed by the CCP Program Manager when the challenge was launched: "What I see here is the combination of a paper project built into something that when people walk by, they can actually visualize what a habitat– What a house on Mars might look like" [3D119]. These deliverables resulted in what some SMEs called a "purely an architecture study" [3D100, see also 3D96].

For the latter, the highest-scoring areas would be architectural criteria. The formulation team grounded the judging criteria for the Design Competition in the tenets of architectural theory: "firmness, commodity, and delight" [3D7, see also 3D3, 3D8, 2018-05-31]. As such, while the criteria covered a wide range of areas for scoring points, the most important ones covered the novelty of the habitat's conceptual design (or aesthetics) and the design's application of additive construction. Per the rules: "Architectural concept and design approach, Architectural implementation and innovation, and 3-D Print Constructability will have HIGH weight factors" [3D17].

This architectural flavor, combined with the time needed to shape the other technical areas of the challenge, also affected other rules. First and foremost, the

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[13] Note that some 3DPH teams invested upwards of \$800k to participate in Centennial Challenges [3D98]; I use "low" relative to these investments.

materials that the printers would use. This challenge extended the time available to SMEs for creating the rules governing the materials in the wider 3DPH Challenge. As such, the Design Challenge did not place a strong focus on what materials solvers would print with, despite its importance to the system's design[14]. While the rules heavily emphasized NASA's intent to use "mission recycled materials and/or indigenous regolith materials" [3D17, see also 3D13], they did not specify these materials besides stating "in-situ resources" [3D17]. SMEs like Ash, for example, did not think materials were important in this phase: "It was an architectural design, so the materials didn't matter in Phase 1" [3D103].

Second, and in the same vein, the rules gave solvers a lot of freedom in their designs. There were very few rules to constrain the designs to what the SMEs would deem appropriate [2017-07-27]. Notably, the rules prescribed a minimum habitable area of 1000 ft^2. Per Quinn, this number was likely derived from existing NASA studies on human area and volume requirements for specific tasks [3D226, see also 3D17, 3D76]. Additionally, all solutions must allow for "a minimum of three 45 ft^3 (1.3 m^3) spaces" to contain life support equipment for the four astronauts [3D17, see also 2017-07-27, 3D10]. Additionally, with reference materials provided as a guide [3D97], all solutions must also pick the site where their habitat would, ideally, be located [3D17].

However, other Mars-focused rules were optional. Even with the requirement for selecting a habitat location, solvers did not have to tailor their design to the Martian surface [3D17]. Though earlier versions of the rules did require this [3D2, 3D7], the final version asked for an analog habitat structure[15] located on Earth: a "prototype for the one that they'll reside in while on Mars" [3D10, 3D17]. As such, SMEs

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[14] Early drafts of the Design Challenge rules included limits on what kinds of material were fair game for solvers: they stated that solvers would design "using only indigenous materials or with recyclable materials additives" [3D10, see also 3D7, 3D8, 3D9] or even "just plastics" [3D6]. But these constraints were later removed.

[15] After the 3DPH Challenge, NASA NASA Johnson Space Center (JSC) would contract with a 3DPH competitor to design and print such a structure [3D184]; see C.6.3.4. Nevertheless, this design did not direct solvers to address NASA's aims for Martian systems.

did not require solvers to take Martian surface conditions (e.g., vacuum, radiation, temperature, etc.) into account. Additionally, while solvers needed to specify their HVAC and power outlets, detailed electrical, plumbing, and ducting plans were "not required" per the rules [3D17].

C.4.3 Outcomes of the Design Competition

Interviewees differed on the merits of the Design Competition. The CCP touted the strong response and varied out-of-discipline participants; here, it awarded a total of $40k to the winners, with first-place taking home $25k. The winner even collaborated with a NASA team after the competition. However, SMEs on the formulation team (and those involved in later 3DPH phases) were generally skeptical of the solutions submitted. I elaborate below.

C.4.3.1 Reflections on Participation

The Design Competition succeeded in reaching out to non-traditional individuals and organizations. In total, the challenge received close to 165 unique entries[16] [3D72, 3D127, CCP144, P5], with 30 selected to participate in the final round [3D72, 3D127]. These participation levels were unheard of for the CCP's challenges. Per one of the CCP team members, this "[was] unprecedented. [The challenge] worked masterfully for that purpose" [P19]. The solvers—participating as individuals or teams—ran the gamut of hobbyists/independent innovators, start-ups, academic groups, large businesses, and even other space agencies [3D31, 3D127, 3D194]. And while many had a strong background in the space industry, most (finalists) came from the architecture, 3D printing, and design industries [3D26]. In short, SMEs like Fran thought the challenge succeeded in "[getting] a whole bunch of people involved" [3D100].

Additionally, the challenge attracted teams outside of the space industry that

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[16] Available documentation differs in how many teams participated: CCP summary documents describe 162 [3D72], 165 [3D99, 3D127, 3D109], or 167 [P5]; CCP leadership recollections note 164 [P19].

wanted to collaborate with NASA in some capacity. In my interviews, two teams participated in the Design Competition to establish a relationship with NASA SMEs, hoping to pursue future contracts to apply their expertise [3D195, 3D196]. Others likely had the same inclination as well. For example, when I asked one participant—an architect—what types of prizes would have also attracted him to the Design Challenge, his response was: “A real contract or a job with NASA” [3D88]. In short, their participation in the challenge might have been the beginning of their involvement in the space industry.

C.4.3.2 Reflections on Solutions

Teams geared their designs towards the Martian surface, NASA’s real aim, despite its optional requirement in the rules. For example, the top 30 finalists—several times the average number of finalists for Centennial Challenges [P5]—all designed their habitats (and associated printers) with NASA’s application in mind and not the training facility described in the rules [3D26]. Several solvers were delighted at the chance to apply their architectural skills to a design problem they had never encountered before. Solvers I interviewed described how the challenge brought their aerospace and architecture interests together in one challenge [3D197, 3D198, 3D207]. They took NASA’s aims to heart and intended to “come up with a very rational, very hardheaded solution to this problem” of designing habitation systems for Mars [3D196]. To help them in their designs, (some) teams reached out to experts on the Mars environment on an ad-hoc basis [3D156, see also 3D188, 3D195, 3D196].

There was an expectation that participants would bring in state-of-the-art ideas. They would not be burdened by the ways that NASA usually does things. Instead, as one CCP team member described, participants were free to be creative “because they don’t have the thinking constraints that we have. I think that alone is very valuable” [3D104, see also 3D187]. The formulation team made this expectation clear in the rules [3D12, 3D13, 3D17] and the marketing material [3D117, 3D118].

By all accounts, solvers' designs were second to none for communicating NASA's aims for long-duration stays on Mars. Per the SMEs and CCP team members, these showed the public NASA's intent in ways that were more compelling than NASA could achieve [3D71, 3D119]: solvers envisioned structures on Mars where people could live, instead of just surviving in a module [3D187]. Both the formulation team and NASA personnel who observed the challenge regarded the designs—and their associated media products—as nothing short of "beautiful" [3D160, 3D193, 3D187]. A CCP team member concisely summed up the achievement of Phase 1 as follows:

> [The solutions] provided a way for the general public to visualize the designs, the final products, in beautiful concepts that helped NASA communicate what we needed to out of discipline potential participants. This stage helped bring to the public conversation a very complicated subject. [3D193]

However, the challenge's lack of technical requirements in the rules, or judges to vet the solutions, left the relevant SMEs skeptical about the feasibility of the solutions. Simply put, the beauty of the designs and the quality of their media products did not convince the SMEs of the technical value of the solutions. Because of the architectural focus of the challenge, SMEs questioned the fidelity of the solutions. SMEs—both NASA and non-NASA—described this phase as "more kind of a concept" [3D80], where solvers could "make up something that could be a habitat on Mars, and draw a picture of it" [3D88, see also P18, 3D122]. They questioned the methods solvers used in their habitat analyses [3D106]. Referring to the delay in placing rules on the materials used to print, they emphasized how "what [the habitat] looks like is not as important as what it's made of" [3D122].

The skepticism of the solutions stemmed from mismatched expectations of solution content. Specifically, those involved with infusing the architectural focus into the challenge were looking for fundamentally different things than the additive construction SMEs. Here, Quinn described "some tension there between the competition that is focused on architectural concepts and the space exploration people who come at it from different perspectives" [3D80]. As a result, while allowing a lot of leeway for "dreamers," this phase lacked the guide rails to ensure the solutions were rigorous in the eyes of SMEs [3D226].

The lack of (required) details in the solutions, in turn, cast doubt on their potential feasibility. SMEs were much more concerned, especially at this stage, about coming up with designs that would work. Blake, for example, thought: "I don't really care what it looks like, but I want to make sure it doesn't kill me" [3D160]. But the judging criteria and judge's assessments did not elicit, or rank, solutions according to how well they kept astronauts alive [P19]. Along these lines, Quinn recalled asking a fellow formulation team member for their thoughts on the solutions:

> I remember [one SME] talking about the architects, being like, "Oh, this has a high level of— It's very aesthetically pleasing." [This SME] comes at that from a completely different angle. [In their mind,] yeah, this concept art looks pretty, but you couldn't actually ever, ever build this thing. [3D80]

Moreover, seeing these solutions and the skills these teams brought to bear convinced the SMEs that they needed to reach out to different communities for the subsequent phases [3D94].

C.4.3.3 Partnerships Resulting from the Design Competition

One team collaborated with NASA directly after the Design Challenge. The winner—SEARCH+, a team of architecture graduates and practitioners—collaborated with a group at NASA Langley Research Center (LaRC) [3D166, P18]. The LaRC team pursued habitat concepts that used water ice as a construction material [3D171], and it coincided with what the winner used in their design [3D165]. This overlap encouraged the LaRC Team to reach out to the 3DPH team [3D125, P19]. The two would collaborate on a design charrette to revise LaRC's original concept to a habitat [3D38, 3D39]. Here, the LaRC team relied on the 3DPH team's architecture, "graphical art, and human factors" experience to inform the design [3D125, see also 3D37, 3D124, 3D164, 3D165]. The value of this collaboration was approximately $20k [3D212]. Note here that the LaRC team was not involved with the formulation of the 3DPH Challenge [3D125]. And while their designs both used water ice found on Mars, LaRC's design did not rely on additive construction [3D38, 3D39, 3D156].

C.5 Phase 2: The Structural Member Competition

The second phase of the 3DPH Challenge contained the Structural Member Competition. It challenged solvers to (create a system to) print standardized material test items from likely Mars ISRU materials. This competition consisted of three levels, requiring different and more complex objects. Accordingly, the prize pots for these levels were $100k, $500k, and $500k, respectively. While the Structural Member Competition's formulation started in 2015, it did not open until late 2016—it, along with the challenge, underwent a major redirection and reformulation during that time. It held its final level, the head-to-head, in late 2017. See Figure 4 below for a visual summary.

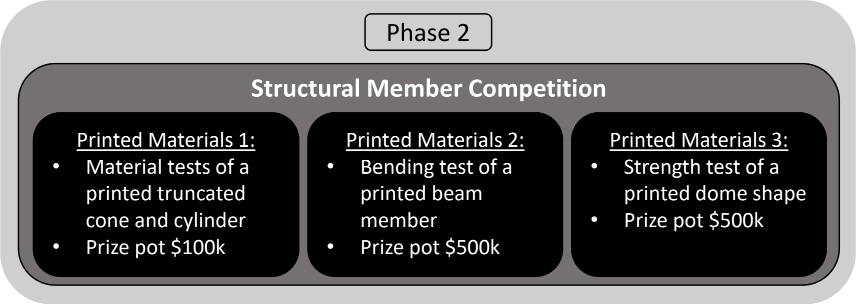

Figure C.4: Summary of Phase 2 of the 3DPH Challenge

C.5.1 Establishing the Structural Member Competition

C.5.1.1 The Focus of Phase 2

Of the technical areas related to additive construction on other planets, what materials would be used as feedstock was the most crucial. It was where the rubber met the road: any mass (and cost) savings of importing materials would depend on how much raw material could be converted to usable construction material. As such, the thrust of this area would be to design and test ways to turn materials available on Mars into a printer feedstock suitable for creating the infrastructure that astronauts need. As Riley described, the Structural Member challenge would "focus on the material that would be used" [3D11]: solvers would "develop a good material" by coming up with a "recipe" suited for NASA's aims, as well as test its physical properties once printed [3D11, 167CCP, 3D103].

Most of the technical uncertainty of the printing system resided with feedstock composition as well. SMEs described the low TRL level of suitable materials relative to the other technical areas [3D95, 3D103]. While NASA SMEs had worked on a range of potential feedstocks separate from the 3DPH Challenge [3D101, 3D130, 3D180], they recognized that many different combinations of materials (with varying mechanisms of printing) would be possible, each presenting different material characteristics [3D122]. The NASA team had not, and likely would not be able to, span the whole space of options. Simply put, materials development was important but difficult, requiring a lot of effort to produce a printable substance [3D101, 3D102]. As Quinn described:

> Something that I always thought was so difficult in this [3DPH Challenge] was the materials development aspect of this. I always thought this could be an entire challenge in itself. Completely independent of the printing and the manufacturing system. Just developing the materials . . . that is an immense challenge [3D101]

Formulating rules for a competition on materials proved to be difficult as well. What feedstock the printer would use had been part of the earliest discussions on what the 3DPH Challenge would address [3D11, 3D21]. However, formulating a rule set that balanced NASA's needs while still allowing participants to show novel solutions proved difficult, as mentioned in C.4.1.2. The Design Competition gave SMEs the time and lessons they needed to structure this competition. In the end, the Structural Member Competition would incentivize solvers to design and demonstrate the basic technologies of printing something on the surface of Mars. Per a formulation team member, solvers would "come up with a, quote, concrete, and you can debate what that term means, to be made out of material that you can find on Mars and . . . print with that material in a rather complicated shape" [3D88]. In short, develop the feedstock material and, in parallel, develop a robotic system that could deposit this material in prespecified shapes [3D69].

C.5.1.2 Refocusing the 3DPH Challenge in Phase 2

SMEs wanted to target a different audience for this phase based on the participation in the Design Competition. The previous phase successfully tapped into the 3D printer hobbyists, architects, and designers. But despite the enthusiasm and work solvers displayed in the first phase, SMEs did not think that these kinds of solvers possessed the skills to address NASA's technical uncertainties. Namely, while their design and 3D printing skills were relevant to the technology, SMEs estimated that these communities lacked the material development and robotics skills needed to create large-scale printing systems. Instead, they estimated that the relevant skills would reside (broadly) in the construction industry, likely due to their cooperation with USACE and the ACME project. Ash described their thinking at the time as follows:

> . . . quickly we realized that [the maker community in Phase 1] was not the right kind of crowd because they were involved with small-scale 3D printing, and what we were doing was large-scale 3D printing, which is a whole different thing. It's more involved with the construction industry, with civil engineering and construction. After Phase 1, we realized that, and we revectored the whole competition. To a new target audience. [3D94]

The construction industry pivot impacted who solved *and* who formulated this competition. To get help doing both of those things, members of the challenge team started reaching out to potentially interested entities, both inside and outside NASA [3D27, 3D105, 3D121]. They reached out to members of the ACME project, who—in turn—connected the challenge to their project partners. SMEs also showcased the challenge at public events to spark interest in the challenge. These efforts were successful and managed to form crucial partnerships for the challenge [CCP71]. Here, Ash described the importance of partnerships outside NASA: "... and that's how we got it all going again. We got Bechtel onboard. We got Caterpillar onboard, VC– So that's how we got it going, by reaching out to external industry and not the space industry" [3D94].

For the subsequent phases, the 3DPH Challenge partnered with six external organizations. These were Bradley University, Caterpillar, Bechtel, Brick and Mortar Ventures, the American Concrete Institute, and the United States Army Corps of Engineers (USACE) Engineer Research and Development Center [3D31, 3D189]. These were no strangers to additive construction technology: some of them had already collaborated with NASA on previous projects [3D27], but most had been following these technologies for several years [3D147, 3D150]. These partners supported the competition's administration, provided monetary and in-kind sponsorship, and assigned a number of their experts to help formulate the rules [3D108].

C.5.2 Formulating the Structural Member Competition's Problem(s)

C.5.2.1 Deliverables

This competition's focus was developing new feedstock materials, whose performance depends on the material's characteristics and the print process. Additive construction, like additive manufacturing, is an area where one cannot determine a material's characteristics separate from how the test sample was made. Different combinations of materials will produce feedstocks with varying properties. The material's bulk properties–like compression or tensile strength–are measured via an object created in layers of that feedstock. As a result, even high-performing materials can result in low-performing objects if the print process is lacking. For example, waiting too long to lay down a fresh bead of (cement) feedstock on top of a previous layer will impede their adhesion [3D89]. Then, the printed object might behave like two objects instead of one.

NASA SMEs, and likely others in the additive construction industry, create models to describe these interactions. But, at least at NASA, these are specific to Portland cement feedstocks—a common construction material [3D89]. These relationships, and the models that build on them, might change with different materials, print processes, or object shapes [3D89]. Blake, as an additive construction SME, described how uncertainty is introduced by a different printing process even when the material is the same:

> If you have a very well-defined bead and you put another very well-defined bead on top you know exactly what your bonding surface is, and you can calculate strength. A lot of times [additive construction companies] print straight down, so the bead squishes out and the bead contact surface area changes constantly. You can estimate an average, but you really don't know. [3D89]

Solvers demonstrating their feedstocks via printing was crucial for verifying the materials' performance. NASA and non-NASA SMEs hoped that these tests would "help us get to a base understanding of the materials themselves" [3D87]. None of these exceeded an area of 1 m^2—these were desktop-scale objects. Solvers would also provide documentation related to their feedstock designs.

C.5.2.2 Feedstock Composition

In contrast to Phase 1's open approach to feedstock material options, Phase 2 focused heavily on polymers. In fact, the earliest drafts of the Structural Member competition rules imagined solvers would focus exclusively; this idea persisted at least up to the launch of the Design Challenge [3D6, 3D11,3D118]. This focus stemmed from the NASA SMEs' contextual knowledge and their work on feedstock suitable for planetary surfaces. Specifically, SMEs at KSC believed that (various) polymers would be particularly effective as a material to bind the regolith material aggregate available on the surface [3D103, 3D137]. When heated, polymer flows like a viscous liquid, allowing the printer to deposit it and the regolith aggregate in layers. Per the SMEs, several factors weigh in this feedstock's favor compared to other types of material: a polymer feedstock requires a relatively low amount of power to heat it to a printable state; its print process is more easily controlled compared to other additive construction methods; it uses no water—a precious resource on Mars; it does not suffer from boil off in vacuum conditions; it offers some radiation protection; and, it is available immediately after landing (in the form of packing materials) or can be manufactured using in-situ materials [3D11, 3D25, 3D92, 3D94, 3D103, 3D137, 3D185, 3D227]. Additionally, the KSC SMEs were developing a polymer feedstock and its printer as part of the ACME project; they successfully demonstrated their printing system while Phase 2 was being formulated [3D130, 3D181]. As such, SMEs heavily preferred polymers due to their estimated performance combined with their in-house experience with this kind of feedstock. One SME on the formulation team described how this preference influenced how they wrote the rules:

> In Phase 2, we pushed hard on using polymers because it was feasible. It was a feasible solution that was really quite good. And I saw that from the work in [the lab], so [we] pushed on that pretty hard[17]

The SMEs' push for polymer-based solutions resulted in the rules favoring those designs. Though later iterations of the rules would broaden the material options for solvers, SMEs would still consider (further) demonstrating the feasibility of polymers as "one of the goals of the competition" [3D94, see also 3D6]. Specifically, the preference influenced the scoring weights for the choice of (constituent) feedstock materials and

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[17] Reference withheld to maintain interviewee's anonymity.

the proportion of their mass (mass ratio). I explain these below.

Feedstock materials SMEs' material preferences drove the rules on the feasibility of feedstock materials. In general, the SMEs wanted solvers to explore potential materials and their different forms for printing [3D122]. As Quinn stated about participating in the Structural Member Competition: "you actually had to do materials development as part of that challenge" [3D80]. To define and bound what solvers would explore for this competition, the formulation team enlisted the help of NASA SMEs—experts in Martian geology and polymers for space missions [3D11, 3D24, 3D36]. These focused on what would be available to the crew and their printing systems once they landed.

Here, several knowledge areas intersect and produce a large materials tradespace. First, Martian geology: Mars has an abundance of rocks, sand, and sediment types; water can be accessed in the form of ice or brines [3D11, 3D24, 3D102, 3D122]. Second, waste or excess materials upon launch: a slew of launch packing materials can be recycled into usable polymers [3D25, 3D80, 3D11, 3D122]. Lastly, additives that (for now) must be brought from earth to create a viable feedstock [3D21, 3D25]. Combined, these form many potential options for feedstocks, with various ways of printing them.

SMEs' extensive contextual and organizational knowledge played a role in narrowing this space. Here, the abundance of specific polymers on cargo missions (to the ISS), behavior of certain materials in a vacuum environment, and the ease of accessing certain materials on the surface shaped the material tradespace. [3D91, 3D92, 3D96, 3D93, 3D102]. Based on these criteria, two materials came into focus: low-density polyethylene (LDPE), per its abundance in the waste streams of current ISS missions; and basalt igneous rock, per its abundance on Mars (barring the use of a dedicated—but much more expensive—Martian soil simulant) [3D226]. Additionally, SMEs knew that certain materials—particularly water—would be so valuable to sustain the crew that using it as a printing material would be risky [3D11, 3D96]. Quinn stated this position as follows: “I think we would never use water for construction purposes because it’s scarce, and you would have higher mission priorities and uses for that water” [3D80].

But SMEs did not just know what materials would be available. Their knowledge also dictated preferences of certain materials over others, which translated into a preference for certain feedstocks. SMEs’ preferences would also affect their assessment of the feedstock’s feasibility. For example, a feedstock that used water would be less desirable than one that did not.

SMEs embedded their preferences in their competition’s scoring system. Here, the formulation team hoped it would push solvers to design feedstocks that SMEs believed would be more feasible. Even in early drafts of the rules, SMEs stated that they “need[ed] a rubric for determining winner of this portion of the [challenge]. Must favor the use of planetary indigenous materials” [3D20, see also 3D110, 3D12]. To do this, SMEs designed a “sliding scale” where the preferred materials[18] received a higher weighting than others [3D91, 3D94, 3D95, 3D96, 3D103, 3D122, P3]. Solvers would stand a greater chance of winning if they designed feedstocks with materials that SMEs preferred: the weights would apply to the mass fractions of each material in the solvers’ feedstock and played a significant role in the solvers’ final scores [3D23]. At the top end of the weighting scheme, receiving the highest score per mass fraction, were LDPE and (crushed) basaltic igneous rock, in line with the SMEs’ preferences.

Similarly, the weighting system would also disincentivize certain materials through scoring penalties. In line with the preferences listed above, SMEs applied these penalties to discourage solutions that did not “close the manufacturing loop, [or] doesn’t bring in recycling potential, [or] material reuse,” per Quinn [3D80]. For example, they included (severe) negative weights for water and specialized, imported materials to make the feedstock work [3D23, 3D25, 3D91, 3D93]. Likewise, using

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[18] The scale in the rules also explicitly labeled the options that NASA wanted with arrows and language like “most relevant” to further emphasize their importance [3D23].

off-the-shelf printing feedstocks–e.g., Portland cement–would not be allowed[19] [3D36, 3D80].

SMEs hoped that the incentives (and disincentives) would nudge solvers towards finding viable feedstocks while allowing teams that could not carry out this exploration to participate. Despite their stated preferences, they did not explicitly forbid any unwanted materials; SMEs believed it was important not to be too prescriptive in the rules [3D95, 3D88, 3D103, 3D122]. By relying on the (dis)incentives instead of exclusion, teams with a terrestrial focus would still see the competition as an opportunity to fulfill their goals—additive construction's potential for efficiency and sustainability in the construction industry resonated strongly with the challenge's partners [3D122, 3D21, 3D94]. SMEs believed that this struck a balance between their planetary additive construction aims and those that terrestrial players aimed for. Ash described this balance as follows:

> So, those were the two goals we were trying to align: the terrestrial benefit and the space benefit. The difficulty was to try and come up with a set of materials that we would score without constraining the competitors. We really didn't want to tell them, "You can't use Portland cement, [or] a certain material, [or] water." We didn't want to constrain them in any way possible. We wanted freedom of thought. That's where we came up with a sliding scale where we give a factor, which is a number that varies with applicability to indigenous materials that you can find in space. ... And it's proven to be very successful. [3D94]

Feedstock ratio SMEs' material preferences also drove rules emphasizing the usage of Martian materials. Recall that most cost savings related to ISRU stem from using mass available at the destination versus launching that from Earth. If a team's feedstock recipe only required a small percentage of in-situ material, most of its mass would still need to be transported there. The solution would, thus, fall short of the

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[19] SMEs, like Quinn, stated that this was meant to discourage teams from, for example, going "to Home Depot and [buying] a bag of cement" to use as their feedstock [3D36]. Developing materials suited for Martian conditions was a fundamental part of this competition and solely relying on existing feedstocks was not going to cut it [3D80]. However, there were no such restrictions on Portland cement's constituent materials.

objectives that SMEs envisioned [3D24, 3D102]. So, to avoid these kinds of feedstocks, SMEs focused on the ratio of ingredients in the feedstock "recipe" to emphasize the usage of in-situ materials [3D1]. As Finley described, they were "just trying to get as much ISRU material in there" [3D24].

SMEs at KSC drew on their experience and experiments to determine the rules. Per above, a low percentage of in-situ material in a feedstock and the solution would not adequately satisfy NASA's aims. However, too high a percentage might result in a feedstock that does not bind or is otherwise not feasible. While SMEs wanted to push solvers towards high fractions of in-situ material usage in their feedstocks, they also wanted to ensure that they did not overshoot this limit. So, to inform the rules, they experimented to understand what fractions of in-situ materials would be feasible. Per one of the SMEs: "we were basically trying to complete the challenge ourselves just ahead of when the actual challenge was happening. That gave us a lot of insight into what is possible or what is not possible" [3D185].

Here, the SMEs decided on a minimum ratio based on their work with polymer-based feedstocks. These ratios are calculated as the fractions of binder to aggregate–in this case, polymer to regolith. While the existing literature and SMEs' previous work showed that a wide range of this ratio was possible, they narrowed it down to a maximum of 30% binder and a minimum of 70% aggregate [3D24, 3D102, 3D103]. This ratio pushed the known limits of how little binder could be added while remaining printable [3D226]. As such, SMEs experimented with various ratios in-house to ensure that this requirement produced a feedstock that would bind its aggregate [3D94]. At the time, Ash was asked whether the rules were realistic, and here is how they described the process of confirming them:

> We went back to the lab, we tried it out, and said, "yeah, 70-30 works. Can it go lower than 70-30?" We did a few more tests and turns out that anything lower than 15% wasn't really working. Any higher than 30 was probably too much binder. So that's how we confirmed that we had good rules. [3D103, see also 3D185]

The 70-30 rule would force the usage of in-situ materials through the high fraction of aggregate materials. Since SMEs estimated that these kinds of feedstocks would use Martian regolith as their aggregate, a high fraction of aggregate would translate into a high usage of in-situ materials—fulfilling NASA's ISRU goals of launching less mass. However, while this rule stemmed from SMEs' work and experiments with polymer-based feedstocks, it would apply to all solutions equally [3D102]. And, per the rules, a "failure to meet this minimum requirement [would] result in disqualification" [3D112, see also 3D23, 3D12].

C.5.2.3 Printed Material Characterization

In addition to rules surrounding the design of the feedstocks, SMEs also created rules surrounding their performance. Specifically, understanding the mechanical properties of prints with "multiple materials" [3D2, 3D20]. These are needed to understand how materials would behave as part of a structure and further design NASA's systems. For Phase 2, they selected properties that SMEs considered a "first gate" [3D93, 3D101]. Additionally, to ensure efficient and safe construction using these materials, solvers would need to consider (Martian) environmental factors that would impact their materials' mechanical properties. I elaborate below.

Structural performance In the Structural Member Competition, SMEs focused on the materials' basic structural properties [3D101]—material strength, its ability to be printed at high angles, and its tolerances when set. In all, solvers would print a short cylinder, a beam, and a truncated cone. These shapes would then be subjected to compressive, flexural, and their own loads to determine the printed material's strength [3D20, 3D93, 3D101].

Structural performance: Material strength The SMEs drew heavily on standards from the construction industry for their strength tests: the shapes corresponded with ASTM C39, ASTM C78, and (a simile to) ASTM C143, respectively. Despite being designed for concrete, the SMEs appreciated their accessibility and long history. First, these standard tests are used very widely. SMEs "could tell the competitors they could go to any kind of lab to certify the results" as many facilities, both in the United States and internationally, use these to test materials [3D103, see also 3D96]. SMEs reasoned that this availability would bring solvers' testing costs down, thus (potentially) lowering their costs to participate [3D93]. In contrast, standards for testing additively manufactured parts are only now being developed; those that exist have seen very limited usage [3D226]. Second, these standard tests are well-known. Ash related that part of the reason why they "settled on using standard engineering tests [is] because that's what most civil engineers use" [3D103]. Their widespread usage and well-understood behavior increased SMEs' confidence in these tests. SMEs saw them as a first step in characterizing a new material with unknown characteristics. Per Stevie[20], a non-NASA SME from the construction industry who was also part of the formulation team:

> We set the rules of the challenge to the standards that exist today because that's what we know [and] because they're proven ways of testing a specific parameter of a material. As we get into exploring new materials, we start by testing them in the same way. [3D87]

These strength measurements would be the primary yardstick for performance across all levels of the Structural Member competition. The stronger a solver's material was in the tests, the more points they would be awarded; their feedstock recipe would moderate these points, producing their final score [3D23].

However, the SMEs understood that these standard tests would not measure these characteristics accurately for all materials. The standard tests were designed for Portland cement concrete. They were not meant to test the (kinds) of materials that solvers would be creating, especially those using a polymer as a binder [3D93]. The

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[20] A pseudonym.

tests were, at best, a best-fit standard: intended to provide a uniform measure instead of tailoring to each material that could be submitted [3D93, 3D92]. SMEs knew that they were compromising on the accuracy of the performance of the feedstocks based on the standard measures [3D101]. Ash estimated that "in some cases [the tests] were appropriate, and in some cases, they weren't. But mostly they were" [3D103]. The SMEs saw these inaccuracies as a better alternative than a slew of different tests better suited to the material families submitted by the solvers. The differences in measurement techniques might raise questions of fairness among solvers, which the SMEs wanted to avoid. Finley described their concern as follows: "What we didn't want to have to do is make case-specific decisions on standards and scoring for every team." [3D93].

Structural performance: Material overhang For the final level of the Structural Member challenge, solvers printed a dome designed by the judges [3D23, 3D110]. This dome was challenging for two reasons. First, the top of the dome was horizontal [3D23, 3D103]. Domes, cylinders, or torii maximize inside volume while reducing pressure stresses, making them ideal for habitats on other planets [3D103]. But as the slope increases, the horizontal surface area for the next layer of material reduces. When the slope is zero (or horizontal), the layers connect horizontally and might fall if there is no support.

Second, no supporting structures were allowed in the object after printing [3D23], maximizing the useable area within the habitat [3D103, 3D105]. Usually, these shapes would require support structures for the layers at the top. So, printing the structure without any supporting material seemed impossible; a potential participant even complained that "an FDM-type 3D Printing process could not build this structure without a support structure" [3D122]. However, NASA guidelines for additively manufactured parts advise against having support structures due to the dangers of debris within crewed cabins [3D226]. Additionally, SMEs saw these supports as a waste of the interior space [3D122]. As such, they required that the final shape did not have any, nor deviate from the model in other ways [3D93, 3D96]. As such, the only option, *seemingly*, was to autonomously remove the support structures before the print was finished [3D23, 3D103, 3D122]. SMEs saw this as a difficult task that was important to maintain. Ash described their position as follows: "if we had a competition and allowed support structures, we wouldn't be advancing the state of the technology. It would be the same as everyone would be doing today" [3D103].

Thus, the dome would test the solvers' material and printing capabilities. SMEs stated that they "intended for this to be a difficult structure to print" [3D122]. The solvers' printing system would need to be robust enough to print the dome shape as modeled, relying on either their materials or robotics expertise to dictate their solving approach. For example, others believed that this dome would be hard to print. But despite its difficulty, SMEs estimated—like Ash states below—that the solvers could somehow accomplish this.

> You have to push the boundaries. If it's completely feasible, then there's no point in having the competition. So, you have to get to something that you're 90% can be done, but you're 10% not sure. And that was [Phase 2's] dome." [3D103]

Structural performance: Tolerances Lastly, SMEs also set tolerance criteria on the printed shapes to assess the accuracy of the printing systems. In general, manufacturing an object to a certain accuracy is crucial. If it does not adhere to the required dimensions, it may not fit within its allotted space or perform as intended. This matters for additive construction as well: the imprecision of printing could produce an object that does not conform to what is expected. Here, its dimensions could depend on how neatly a printer can lay down a bead and how that layer behaves once it is laid down [3D89]. Additionally, different materials contract and expand at different rates when exposed to a temperature gradient, meaning the object's final dimensions might not be the same as the as-printed ones [3D106, 3D185]. In this vein, SMEs wanted to determine the accuracy of solvers' printing systems.

SMEs imposed a maximum allowable deviation on each object, determining whether their accuracy was allowable. The truncated cone, cylinder, and width and height of the beam received a tolerance of + 7 mm. The length of the beam and the dome structure would receive a tolerance of +/- 7 mm. If solvers' objects did not comply with these tolerances, they would be required to produce new ones or face a zero score for that level [2017-03-02]. At the final level (where printing time was severely limited), the number and magnitude of the tolerance violations could severely reduce the final score—the judges would have the final say here [2017-05-18].

Environmental performance In the Structural Member Competition, SMEs considered including two essential areas relating to the material's performance in the Martian environment: its behavior while exposed to vacuum and its ability to shield against radiation[21]. Their effects on the feedstock's behavior are important to understand and mitigate where needed [3D103, 3D82]. But while SMEs initially considered testing solvers' solutions via analyses, they dropped both criteria from the rules of Phase 2 [3D92].

Environmental performance: Vacuum Since the Martian atmosphere is less dense than Earth's, "vapor pressure is a huge issue," as Finley explained [3D102]. Under these conditions, liquid in the feedstock might boil and evaporate when printed. The printed object will have irregular voids instead of being a solid, and its strength would be considerably reduced [3D65, 3D102, 3D160]. Indeed, experiments conducted by SMEs showed that the material would foam up and form a "muffin top," retaining only a fraction of its material strength [3D103, see also 3D65]. Referring to the performance of that feedstock in those conditions, Finley stated, "it didn't work too

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[21] The latter would be revisited in Phase 3.

well" [3D95, see also 3D103].

Despite its significant influence on the material's printing behavior, however, SMEs decided not to subject solvers to complying with this requirement. In doing so, SMEs would lose information on whether and how the material would retain its strength under these conditions [3D82, 3D101]. And since it would not be tested in the relevant environment, it would not mature per the TRL scale [3D94]. Nevertheless, there were several reasons for this decision [3D92, 3D101, 3D102, 3D103]. First, SMEs strongly believed that any such testing requirements would be too costly to impose on solvers if they had to access vacuum chambers themselves [3D80,3D94, 3D103, 3D102]. Ash thought that "it would have probably shut the competition down if we had done that" [3D94]. Second, and relatedly, using one of NASA's test chambers would exceed the 3DPH Challenge's budget [3D101, 3D160]. And lastly, SMEs thought it was too specialized a requirement to impose on teams that were not in the space industry. Instead, SMEs saw it as their responsibility to design towards that environment. As Quinn put it, it was "something that NASA would do on our side" [3D93].

Environmental performance: Radiation The Martian atmosphere does not protect against radiation as Earth's does. This makes it a serious threat to the crew's lives [3D11, 3D93, 3D124]. Thus, structures will need to adequately shield the crew from radiation to be considered habitable. [3D6, 3D124].

However, the SMEs decided not to require solvers to design or test to these conditions. Like the vacuum conditions, SMEs believed that these requirements were quite specialized. Once again, Quinn believed that it would be NASA's responsibility to iterate on "some high potential design or material" in collaboration with the designer [3D93]. As such, the SMEs "[didn't] define radiative environments in the rules, so this [was] really outside the scope of [their] evaluation of materials and structures," per contemporaneous email traffic [3D92].

Environmental performance: Materials scale concerning vacuum and radiation performance The rules for Phase 2 lacked analyses or tests for the Martian environment. However, the materials scale described earlier would still push solvers towards material choices that SMEs believed were more suitable. Specifically, KSC SMEs favored polymers as a construction material partly because they estimated that it would perform better in the Martian atmosphere than hydraulic cement concrete [3D94, 3D102]. First, polymer binders did not use water. Because they would not suffer from the boil-off problem, SMEs estimated that they would outperform the hydraulic cement concretes. Ash, for example, believed that though "the polymer concretes have never been tested in vacuum, I think that they would do better than the hydraulic concretes" [3D94]. Second, plastics stopped radiation [3D6]. Thus, their use as a building material would include significant protection and its structural functions [3D11]. So, while polymers were already highly rated for their abundance on these missions, the scale *also coincided* with their estimated performance under Mars' conditions. The rules, thus, incentivized solvers towards the options that SMEs believed were better across a broad range of parameters.

C.5.2.4 Printer Form Factor

The printer's form factor—its footprint and printing method—was also an area SMEs considered gearing towards their application.

Printer footprint For NASA, systems with large footprints are much more costly to field and operate. Their mass and volume mean higher launch costs and more space on a rocket [3D11]. While not as crucial in terrestrial applications, NASA's external partners recognized the benefits of space-saving as well [3D11, 3D180]. Because of this, SMEs considered explicitly restricting the printing system's footprint [3D6, 3D22] or, at least, incentivizing smaller printers [3D11]. For example, one SME on the formulation team commented the following on an early draft of the Structural Member

Competition rules: "[W]e should limit the packaged/shipping size of the system. We don't want a great system that could never be moved to a disaster relief area" [3D6].

However, SMEs pushed any such rule outside the context of the 3DPH Challenge. The formulation team decided not to impose any requirement from the space industry on the footprint of the printers. They believed that it would distract from the more important task of demonstrating the printer [3D105]. Instead, the team decided to push the more stringent space requirements until later in the development process. The Structural Member Competition rules merely specified that the printer had to be transported over regular roads [3D23]. Harper summarized their decision not to limit the printer's footprint as follows: "that's not where we want[ed] the teams to spend their time, trying to miniaturize it, trying to– You know? That can happen later once you've proven the technology" [3D105].

Printing methods Mars' reduced gravity environment also imposed difficulties on the printer design. These conditions mean that materials—particularly powders—do not settle as they do on Earth. Powder beds are a common method of 3D printing for terrestrial applications [3D36]. But even with (non-NASA) microgravity research is being done on powder bed printing [3D226], NASA SMEs did not think they could work in their setting. In particular, loose particulate matter during printing could more easily lead to combustion or respiration hazards [3D192, 3D36, 3D91]. Blake put it succinctly: "You can't use a powder bed in microgravity" [3D89]. Additionally, while this method worked well for printing relatively small parts, SMEs did not believe this method could print an object the size of a house [3D95, 3D112, 3D163].

So, SMEs curbed solvers from pursuing architectures that might be familiar to them but (essentially) unsuitable for NASA. The rules explicitly warned against designs that created too much dust or other waste[22] [2017-02-02, 3D112]. SMEs emphasized

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[22] Despite the consensus on the problems with powder beds, SMEs like Quinn expressed an openness to ways of mitigating against the dust issues: "... if you can show us how to manage that— We're

that these could not safely function in a space context, nor were these safe for people near the printer [3D23, 3D36]. SMEs also forbade manual removal of supporting material for the prints, explicitly mentioning that removal of the powder bed around the printed object fell into this category [3D23]. The competition's FAQ followed suit with further clarifications [3D112]. In contemporaneous email traffic, one SME explained this rule to a fellow team member as follows:

> Teams do have to address applicability of their manufacturing system to planetary surface construction, and do receive a score on that criteria (which mostly refers to an assessment of whether the process can operate in a reduced or microgravity environment and was included as a way to discourage use of powder-based systems) [3D92].

C.5.3 Outcomes of the Structural Member Competition

The 3DPH Challenge team saw Phase 2 as a big success. They awarded a total of \$701k across the three levels, with the winners taking home \$80k, \$0K[23], and \$250k, respectively. While the number (and variety) of participants was relatively low, SMEs were pleased with the performance of the solutions. After the competition, both the winner and runner-up feedstocks were further tested in-house and aboard the ISS.

C.5.3.1 Reflections on Participation

While the formulation team's pivot towards the construction industry succeeded in drawing non-space participants, participation was significantly less than the previous one. A total of eight teams participated across the Structural Member competition [3D127]: these solvers submitted at least one solution in one of the three levels. Unlike the Design Competition before it, no non-affiliated teams managed to submit a solution to any level. All teams stemmed from academic or industry backgrounds—five of the former and three of the latter [3D127]. However, like the Design Competition, most

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open to that if you can come to us with an approach of how you would address it, manage it, and ensure safety. . . . It's a challenge not to be too prescriptive" [3D36].

[23] No prize money could be awarded to a non-US team, but second place was awarded \$67k.

participants were not previously part of the space industry: only two described prior space experiences [3D207, 3D208]. The others were decidedly outsiders to this industry [3D90]; these participants talked about how they always dreamed about working with NASA, something that would be “freaking amazing” [3D209]. The teams winnowed down to three in the final round: two academic teams and one industry team.

One cause of the relatively low participation was the high cost of solving. Many teams complained that they could not afford to complete the challenge: developing and testing the hardware required for the deliverables of the competition was expensive. Even with the thought that went into reducing the barriers to entry, SMEs on the formulation team acknowledged that “it was a pretty big physical investment,” per Harper [3D105]. In a survey after the 3DPH Challenge, solvers reported that developing their materials and creating the associated printer cost more than they were willing to pay. One team who dropped out in Phase 2 described why they stopped participating: “The farther along the competition got, the more expensive it got to participate. We ended up dropping out of the challenge because it was too expensive to continue” [3D98]. Several other teams echoed this sentiment and described the difficulties of acquiring enough capital to fund their developments.

C.5.3.2 Reflections on Solutions

Solvers demonstrated novel, high-performing materials Participants in this competition produced high-performing materials and meaningful insights for the SMEs. Their innovations covered both hydraulic cement and polymer-based feedstocks. For the former, teams recreated or modified the Portland cement recipe using materials available on Mars. For example, one team drew on their organization’s deep experience with Portland cement [3D210]. From their perspective, the risk of pivoting to, from their perspective, an unknown material was too great. Instead, they used their expertise to create a known material in an unfamiliar environment. Per one team member: “It’s real exciting to be developing something new. But in this case, we said, ‘ok, we know this [material] can do XYZ, how do we get to do it in this application?’” [3D210]. To prove that their recipe could produce the same performance as stock Portland cement, SMEs required that the team demonstrate its performance within acceptable bounds [2017-07-13]. As a result, the team “earned the right and was allowed by the judges to use Portland cement for the competition with a positive 3DP Factor defined by the indigenous factors instead of the negative penalty due for Portland cement” [3D99]. Another team had the same idea but took a different tack: it developed an equivalent to Portland cement that used much less water to achieve a similar material [3D48, 3D156]. Per reports, the SMEs considered these a “significant advancement in the demonstration of cement production from Mars indigenous materials” [P3, 3D99].

For the latter, the winning team—a partnership between Branch Technologies and Techmer PM–produced a high-performing feedstock by combining polyethylene terephthalate glycol (PETG) thermoplastic as a binder with basalt glass fiber as aggregate [3D73, 3D140]. Both binder and aggregate were highly rated materials on the competition’s material scale, though using fibered basalt was new to the SMEs [3D73]. Its performance was surprising for two reasons. First, the combination of materials and printing quality also significantly outperformed its hydraulic cement competitors. According to a report on the challenge, the winning polymer concrete feedstock demonstrated a material strength approximately “23 times higher” than typical Portland cements [3D73]. Across the board, SMEs believed “it’s a very high strength blend” [3D80, see also 3D94]. More generally, teams that pursued polymer-feedstock options helped “prove out [their] efficacy” in the eyes of the SMEs [3D226].

Second, SMEs were impressed with the printing capabilities displayed by Branch. Ash even exclaimed that they achieved “the holy grail in 3D printing” [3D94]. Conventional wisdom required level 3's dome to be printed with support structures. However, the winning team printed their material horizontally without supports—something that the NASA SMEs did not think these kinds of materials could do. For example, Ash stated they had "never seen it before when you horizontally print, and it doesn't collapse or slump" [3D103]. Jude saw the solvers' performance and remembered thinking, "What just happened! How did they do that! We [as NASA] wouldn't be able to do that!" [3D185]. Across the formulation team, SMEs considered the feedstock, in their words, a "breakthrough" [3D103], an "inspiration to the [KSC] team" [3D130], a "major outcome" [3D80], "absolutely revolutionary" [3D94], and "incredible" [3D93]. The material's performance meant that the team's printing system could produce complex shapes without the complex robotic architecture that other teams required to produce the same shape.

More generally, SMEs were happy that the rules pushed solvers to explore material combinations that they believed were more favorable to their ends. While NASA already had projects exploring planetary additive construction feedstocks and processes [3D63, 3D65], SMEs believed that the efforts of the solvers would help rather than replace them. In line with this sentiment, Quinn described how they saw "the efforts as complementary, rather than competitive" [3D36]. It pushed teams to explore the kinds of designs the SMEs were interested in. Some teams even reported switching from materials they had a lot of experience with to those that gave them a better score [3D36, 3D209]. Overall, SMEs regarded material innovations as a big return on shaping the rules. Quinn, in particular, described how satisfied they were with the overall progress on materials during this phase:

> I think the teams came up with really— Especially in Phase 2, [they] came up with really interesting and different [material] formulations. ... I think that [Branch's] material [was] just a good, good outcome. And I think [Branch's partner] Techmer might make that material commercially available now. It's a very high strength blend. [3D80]

Solvers demonstrated novel autonomous systems Teams whose material could not print horizontally developed novel workarounds to produce the dome shape that the SMEs had laid out. The runner-up—Penn State University (PSU)—impressed the SMEs by demonstrating autonomous printing and removing the needed supporting material [3D189, 3D99]. While a primary robotic arm printed the dome, the team used a second arm to break apart and pick out their supports—thus never needing a manual intervention [3D103]. One of CCP's weekly reports described the "novel, robotic method" [3D189] like this:

> Penn State's autonomous removal of the supports they used to print the dome was also novel and a technique they might not otherwise have been developed outside the framework of this competition [CCP147, see also 3D226]

Solution infusion into NASA projects NASA projects infused two solver-created materials following the Structural Member Competition. The winner's polymer-based feedstock and the runner-up's hydraulic cement feedstock were used in tests or experiments: the KSC team took the former and the MSFC team the latter. This follow-on testing would allow SMEs to characterize the material more thoroughly than the competition. Finley described it as "a direct infusion. We get more information out of it. We can start looking at using that in our systems" [3D95, see also 3D162].

For the former, the SMEs used the solver's feedstock in the in-house polymer printer and adopted their feedstock processing method. First, given the incredible performance of the material in the competition, SMEs were eager to test it in-house [3D162, 3D185]. They procured a batch from the solver (their material supplier, to be exact) and tested it in their lab [3D73, 3D80, 3D99], requiring only minor modifications to their existing printer [3D185]. They learned valuable lessons about the materials printed behavior from their tests [3D130].

Second, the material processing method demonstrated by two teams promised to solve NASA's feedstock homogeneity and safety problems. KSC's approach had been to reduce the raw materials to a powder and combine these at the printhead (while printing) [3D130]. However, it was hard to maintain a homogenous mix of the different raw material powders [3D130]. Additionally, SMEs became concerned about the combustibility of handling powder [3D91]. However, these problems were alleviated by pre-processing the raw materials into homogeneous feedstock pellets before printing [3D91, 3D185, 3D189, P3]. Per a technical report after the competition: "The pellets developed in the competition by several teams eliminate these safety hazards have given NASA important insight into how to use these materials while minimizing danger to mission, crew, and equipment" [3D73].

For the latter, members of the runner-up team sent samples of the material to the ISS for further characterization in microgravity. The team's material had been a hydraulic cement concrete, whose behavior had never been studied in the space environment, specifically exploring the effect of gravity [3D167]. As such, the team developed an on-orbit experiment to observe differences in the feedstock's reactions [3D156, 3D169, 3D174]. Quinn described this as yet another "really good" outcome [3D80].

Solution shortcomings Despite these innovations, some solutions fell short of what the SMEs expected—even the novel ones. First, several teams could not meet the mandated high bar for indigenous Martian material. Recall that solvers' feedstocks needed to include at least 70% indigenous materials. This value stemmed from KSC in-house experiments with polymer-based feedstocks. However, complying with this minimum was much harder for teams that took the hydraulic cement route, who thought they could produce a feedstock that could serve their terrestrial uses as well. Specifically, adding that much aggregate made a viable material "difficult" and "hard," per Finley [3D102]. So hard that it affected the team's participation. Across Phase 2, four teams[24] submitted non-compliant solutions—these were rejected [2017-05-04].

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[24] One of these four teams submitted a non-compliant polymer-based feedstock.

Likewise, one team's score suffered greatly solely because of their choice of materials. As Finley described it:

> If a certain team wants to develop their technology along the lines of 3D printing here on earth with Portland cement, . . . they're not going to want to do that planetary composition. And that's ultimately what hurt [one team] in that last round because they scored low on their materials. [3D102]

Second, SMEs doubted the practicality of (some of) the solvers' feedstocks. The material scale had successfully pushed solvers to design feedstocks using materials on Mars. However, the scale did not incorporate more practical concerns like gathering and processing the materials into their usable forms, which would be extremely important for its usage. Finley "was amazed at the lack of addressing the issue of getting these materials in situ also. That was something I was hoping to get more information on from the competitors" [3D102, see also 2017-05-04]. Practicality was also the main concern for the Martian Portland cement recipe. Though novel, it did not address its supply chain considerations. SMEs estimated that it would require large processing facilities with raw material gathered from disparate places "separated by 1000s of km" to create the cement [3D25, see also 3D102]. Quinn summarized that as follows:

> You can technically make [Portland cement] on a planetary surface, but it requires a large manufacturing footprint. There's a lot of mental gymnastics associated with saying: "yes, I can actually make this on a planetary surface, ergo you should consider this as an indigenous material." [3D36]

C.5.3.3 Partnerships Resulting from the Structural Member Competition

Lastly, while SMEs discussed a potential follow-on project with the (level 3) winner, it did not materialize. After the competition, SMEs pushed for a large-scale demonstration of the printing technology. They envisioned printing large water storage tanks as part of KSC's spaceport infrastructure [3D73, 3D137]. However, partly due to other commitments by the solver team, this did not proceed [3D185]. Nevertheless, SMEs were hopeful that such partnerships would eventually materialize. Quoting Quinn: “And I think some of these [teams] may, down the line, work with NASA by virtue of the connections and visibility that they’ve gotten through the competition” [3D36].

C.6 Phase 3: The Virtual Construction and Construction Competitions

C.6.1 Phase 3’s Two Competitions

Phase 3 contained two competitions: the Virtual Construction Competition and the Construction Competition. Participants in the former would design a high-fidelity architectural model of their 3D printed Mars habitat. Across two levels of this competition, participants would increase their model’s fidelity and the required analyses. Both levels of the Virtual Construction Competition offered $100k in prizes.

Participants in the latter would develop and demonstrate a printing system for larger and (more) realistic structures across three levels. Here, each level tested the solvers’ printing systems (feedstock and printer combinations) for their ability to print basic structures to scale (e.g., foundations, pressure vessels). The challenge culminated in a timed print of their habitat designs (scale model) at the Caterpillar Headquarters in Peoria, IL. Per a non-NASA SME on the formulation team, “Phase 3 [was] the most challenging that we’ve had yet” [3D120]. The prize pots for these three levels were $120k, $300k, and $800k, respectively. See C.5 below for a visual summary of this phase.

The two competitions were independent. The deliverables, requirements, and prize awards of one competition did not impact the other. However, participants in the Construction Competition were also required to participate in the Virtual Construction Competition.

The formulation team began their work on this phase in mid-2017. SMEs began

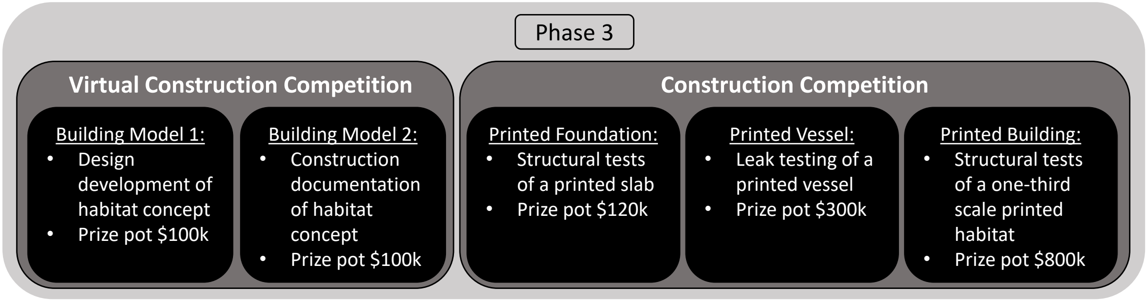

Figure C.5: Summary of Phase 3 of the 3DPH Challenge

formulating the Construction Competition first, then the Virtual Construction Competition in the fall of 2017. Both competitions were opened simultaneously and were held concurrently during 2018 and 2019. The 3DPH Challenge held the final level of Phase 3–the Construction Competition's head-to-head–in the fall of 2019.

Phase 3 would emphasize different areas than the previous phases. Notably, the SMEs deemphasized the importance of materials following a "big internal discussion" [3D80, see also 2017-06-22]. The rules surrounding the feedstock materials in Phase 2 set a high bar, with both good and bad outcomes. They had successfully encouraged the innovations that SMEs were looking for: the Phase 2 winner showed material innovations that took SMEs by surprise. But at the same time, some on the formulation team believed that the rules overconstrained the problem by focusing on polymer binders [3D88]. Additionally, SMEs disqualified several teams that fell short of the stated requirements. Weighing these outcomes, SMEs reconsidered those rules [3D102, 3D73]: while "there [was] general agreement that our Phase 2 materials scale has served us well," the formulation team decided then that these rules needed to be relaxed [2017-06-22, see also 3D80]. Quoting Ash, the formulation team decided: "[L]et's loosen it up for Phase 3.' So, we did" [3D103].

With the deemphasis of materials, SMEs instead shifted the focus towards more important to emphasize areas that had not yet been challenged [3D73]. In particular, both the Virtual Construction competition and the Construction competition would cover three areas of development (coinciding with those described in C.2.2.3) [3D11, 3D16, 3D76, 3D96, 3D107, 2017-07-13, 2017-06-22]. The first was related to the printer's behavior: autonomy. SMEs hoped to minimize human interventions during printing and encourage a close relationship between the virtual model and printed object and printing process. The second was related to what would be printed: large-scale objects. Here they hoped to push solvers to scale up the size of the printed objects from those in Phase 2. And finally, an area related to the performance of the prints: bulk structural properties, like pressure retention and surface finish[25]. SMEs would push solvers to accomplish these through a combination of materials and printing processes.

In the sections below, I further explain these decisions and how they infused into the rules for both the Virtual Construction and Construction competitions.

C.6.2 The Virtual Construction Competition

C.6.2.1 Establishing the Virtual Competition

At the end of Phase 2, some on the formulation team were concerned about participation in the final phase of 3DPH. While the SMEs were pleased with the winner's performance in Phase 2, they acknowledged that the bar for participation was set very high. Members of the formulation team, like Billie[26], knew the task of creating and demonstrating a printer and feedstock system was "difficult" [3D88], requiring a lot of resources on the part of the solvers [3D80, 3D98]. In their estimates, the difficulty would increase by "orders of magnitude" with the scope planned for the construction portion in Phase 3 [3D105]. Here, formulation team members, like Harper, were afraid that few would be able to afford these expenditures, potentially resulting in very few participants in this phase: "there was only going to be a few

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[25] Prints would also be tested for their resistance to impacts, to simulate micrometeorite strikes on Mars. However, the focus of the SMEs—and the points distributions for each level—would be on these two criteria.

[26] A pseudonym.

entities that could probably pull that off. We wanted a broader swath of people to be engaged" [3D105]. As such, some on the formulation team called for something to be done to maintain the interest of solvers that would not be able to complete the physical demonstration [2017-07-20, 2017-06-15].

In response, the formulation team (re)introduced an architectural design challenge as part of Phase 3. Participants would, again, design a habitat built using additive construction technologies. The SME's vision was to launch a complimentary challenge where the barrier to entry was not as high as the construction deliverables required [3D92]. This competition would allow smaller teams—usually individuals—to participate, broadening the amount/range of potential participants [3D76, 3D105]. A design deliverable in Phase 3 would also reinforce the connections to the architecture community that they created in the Design Competition [3D87].

Like the Design Competition, this challenge aimed to explore the potential designs that could be achieved using additive construction [3D69, 3D120]. The focus would be on novel architectural concepts made possible by additive construction and concepts for its layout and operation of the spaces of the habitat (also called its space programming) [3D87, 3D106, 2017-10-26]. One CCP member of the formulation team envisioned it as follows: "maybe there is a big prize, big-scale competition but alongside maybe a smaller scale competition to bring out more ideas" [2017-06-15].

However, this time, the formulation team would implement rules that would (try to) elicit a consistent quality across the solutions. This way, they would—hopefully—avoid the same pushback and dismissal by SMEs in the Design Competition. The formulation team would also make an effort to clarify what they hoped to see in the submissions. Here, they organized two public webinars, where their experts provided a primer on habitat design, explained their models/rules of thumb that NASA used in their work, and what the competition was asking for [3D120, 3D121, 3D32]. These efforts to increase solution quality contrast starkly with the first phase, where the rules simply pointed to the available reference material [3D97].

Lastly, like in Phase 2, the formulation team reached out to entities they thought would be more likely to participate successfully. Specifically, the competition's emphasis on the Building Information Modeling (BIM) modeling tool targeted those who had experience using this tool. For example, the minutes of the formulation teams' meeting described how they reached out to organizations "in the architecture area or construction management/BIM area" for potential solvers because "they do BIM work" [2018-02-08].

C.6.2.2 Formulating the Virtual Competition's Problem(s)

Deliverables Wanting to avoid the ambiguous quality of submissions received in Phase 1, the formulation team took a bigger role in shaping what solvers would submit for this design deliverable. The formulation team wanted to remedy the "tension" that Quinn described in Phase 1: on the one hand, a focus on architecture and design–to get broad ideas and participation; and on the other, a focus on space exploration–to get viable habitat designs in the eyes of the SMEs [3D80]. As such, the SMEs took a harder look at the level of detail required for the habitat concepts, hoping that increasing these would improve the submissions' quality [2017-06-22]. For this, they relied on the construction industry collaborators on the formulation team, who looked to approaches within their industries [3D106].

The team settled on a modeling approach from the construction industry called BIM. This approach creates a high-fidelity, virtual representation of the building's physical and functional components [3D32]. They depict the building's systems data, its lifecycle, and how different disciplines can collaborate on its construction [3D121]. When the construction SMEs on the formulation team suggested this approach for the 3DPH Challenge, BIM had already been a "pretty mature technology in the building world," with an established community of practice[27], per Billie [3D106, see also 3D87].

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[27] The novelty for the BIM community would be applying their approach to create planetary

This community had agreed-upon standards of modeling as well as a vision for a common practice of using these techniques as a digital twin to the physical building [3D32, 3D87, 3D200]. In fact, one member of the 3DPH formulation team was a key contributor in developing the BIM modeling standards [3D200].

The known, accepted standards would force consistency in the maturity of the virtual design. In particular, the Level of Development (LOD) BIM standard provides a ladder of increasing specificity for individual elements in a virtual model [3D200]. The higher up the ladder, the more specific information about the element is expected [3D121]; for example, objects range from a symbolic placeholder lacking a shape or size (at LOD100) to sufficient information to fabricate the element depicted (at LOD400) [3D200]. In addition to modeling static structures, BIM's tools also model the (autonomous) movement of equipment and materials during construction, including the building's components modeled at different levels of development [3D32].

SMEs wanted participants to follow this standard and incentivized them to do so. Billie explained how the standard would result in more detailed models: "We use the jargon 'model discipline.' You have to model things appropriately in place, properly label with a recognized level of development" [3D106]. With this commonality in mind, the rules for the Virtual Construction challenge "were actually written to follow the Level of Development standards," per another construction SME assisting with Phase 3 [3D87]. Specifically, the rules awarded points for how well the submission complied with the information content requirements in the BIM standards for the design's two most important subsystems—its structural components and its life support systems [2018-03-22, 3D32, 3D200]. SMEs assigned about 13% of the points for level 1 to comply with the assigned LOD. In level 2, this was about 10% of the total.

These features would allow SMEs to (more) accurately measure the virtual design's maturity and verify (elements of) that design through simulations of its construction

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structures [3D106].

process [3D201, 3D185]. The formulation team hoped to better control what solvers would be submitting and instilling “more rigor” in the designs, per Billie [3D106]. This way, they would ensure that the “proposed habitats were realistic in design, materials, and construction and able to be manufactured with [additive construction] technologies,” as reports would later detail [3D73].

Design focus Across the two virtual levels, SMEs asked participants to design a habitat yet again. Following the same scenario described in C.4.1, the habitat would need to provide adequate living space for the crew of astronauts for the duration of their mission. Being a design competition, the submissions’ aesthetics were once again important scoring criteria. Architects with “experience serving on judging panels for significant and iconic structures” evaluated these solutions [3D161, see also 3D32]. SMEs assigned a quarter of the total points in level 1 to the design’s aesthetic representation. In level 2, this was approximately 21% of the total.

However, in contrast to the Design Competition, the habitat’s space programming was now a major focus. The criteria evaluated how well the design would perform as a living space for the crew. Stevie[28], a non-NASA member of the formulation team, explained that the criteria would test whether solvers “think through not only the different types of programs, the different types of spaces, they really did think about a person’s experience in terms of . . . [their] public activities and private activities” [3D87, see also 3D106]. It became one of the most important criteria across both levels for the Virtual Construction Competition [3D76]. Its focus was partly in response to the SMEs’ concerns about the habitats’ functionality in the Design Competition: these “had a lot of variability,” per formulation team meeting minutes [2017-06-22]. SMEs assigned a quarter of the total points in level 1 to this criteria. In level 2, this was approximately 21% of the total.

Additionally, the solvers’ submissions would contain significantly more detail than

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[28] A pseudonym.

the Design Competition. In particular, SMEs would focus solvers on three important architectural aspects of their habitat [3D32, 3D120, 3D121]: its structural components, life support systems, and construction process. I explain the rules surrounding these three areas below.

Design focus: Structural components A habitat's structural components provide the enclosure that protects the crew and their equipment [3D32, 3D38, 3D43, 3D120]. The rules specified these as the structure's "foundation, exterior surface, load bearing/pressure retaining walls, etc." [3D76]. In their submissions, solvers would need to show how these components bear the "expected loads" [3D161]: the structure's load as well as its ability to act as a pressure vessel.

The former was related to the loads on the structure caused by Martian physical conditions (e.g., gravity, wind loading) [3D32, 3D76]. While this is a basic requirement for any structure, it is essential here considering the uncertain interactions between (new) feedstocks, material deposition, and habitat geometry.

The latter was related to containing the appropriate atmosphere for the crew's needs, as the Martian atmosphere is less dense than Earth's. While previous Mars mission concepts had incorporated additional structural elements to fulfill this task (e.g., an inflatable membrane) [3D93, 3D87], the SMEs decided on a different approach. As Quinn summarized: "We really wanted to focus this competition on continuous manufacturing, demonstrating a core technology to 3D print an enclosed space, as we wanted pressure retaining structures that were constructed using 3D printing" [3D93]. As such, there was a focus on pushing solvers towards designs and printed objects that were airtight and watertight in both the Virtual and Construction challenges [3D87, see also 3D88, 3D93, 3D107]. In line with containing pressure, SMEs would also push solvers to include, and seal, wall penetrations. Specifically, solvers would design systems to incorporate interfaces with the walls during printing. Similarly, solvers were expected to describe “concepts and methods” for sealing their required penetrations [3D161, 2017-10-26].

The formulation team saw the Virtual Construction Competition as fundamentally a structural competition [3D87, 3D121]. In this vein, the rules required the highest level of maturity for this aspect of the habitat[29]. As one report described it, solvers were to provide “all of the information needed to construct the pressure-retaining and load-bearing portions of the habitat using a large-scale additive manufacturing system” [3D73]. Accordingly, the robustness of these components was also one of the most important scoring criteria. Per meeting minutes, it judged how the submission “documents a practical plan of construction [including its manufacturing processes] as well as habitat suitability for expected loads” [2018-02-15, see also 2017-10-26]. SMEs assigned a quarter of the total points in level 1 to the design’s (structural) robustness. In level 2, this was approximately 21% of the total.

Design focus: Life support systems A habitat’s life support systems sustain the crew inside the habitat [3D32]. In this competition, this system encompassed air, environmental monitoring, and waste [3D121]. Like the life support systems requirements in the Design Competition, solvers were not required to perform their own sizing calculations. Rather, the formulation team required that their designs include three volumes designated for Environmental Control and Life Support System (ECLSS), summing to 45 ft^3 [3D76, 2017-07-27]. In contrast to the Design Competition, however, solvers were required to design the mechanical, electrical, plumbing, and ducting infrastructure to allow the ECLSS system to function [3D121]—this infrastructure was previously optional. SMEs set this LOD at 200: graphical representations within the solvers’ models “with approximate quantities, size, shape, location, and orientation,” per the standard [3D200]. Per the rules, SMEs awarded points for “the presence and

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[29] Note here that while solvers were expected to pick “appropriate” materials to use for their printer’s feedstock, this area was not part of the scoring process like it was in Phase 2, nor were solvers required to document its recipe [3D161, see also 2018-01-11].

practicality" of the design of this subsystem—here, solvers could earn about 13% and 10% of the total score in levels 1 and 2, respectively [3D76].

Design focus: Construction processes In addition to modeling the structure and life support "subsystems" [3D32], the formulation team was also interested in modeling *how* these would be constructed. The formulation team understood that the construction of any habitat would need to be (highly) autonomous considering the risks of, e.g., astronauts' exposure to radiation and during construction [e.g., 3D11, 3D103, 3D124]. In the Virtual Construction Competition, this area had two implementations [3D87, 3D88, 3D92, 3D106, 3D121]: advancing the translation step between the virtual model and the printer's processes (bringing these closer together), as well as simulating the flow of (temporary) facilities, equipment, and materials during the construction process.

The former involved exploring more efficient algorithms to turn the virtual model into a tool path [3D92]. In this translation step, an algorithm "slices" the 3D shape into 2D shapes, then forms a path that the print head follows to deposit its feedstock [3D130, 2018-03-29]. This algorithm considers many factors, including deposition rates, drying or solidification times, real-time sloughing, etc. [3D89]. While this translation is common across all forms of 3D printing, no standard processes exist to make this process easy [3D130, 3D165]: quoting Harper, "the industry is not there yet" [3D96]. Additionally, algorithms that print small objects do not translate into large ones—the latter are especially vulnerable to inaccuracies or errors in the printing process. Specifically, the large object's bulk properties may no longer be uniform over the large distances that the print head travels. As Jude explained, "when you're printing something very big, [the tool path] has a huge impact on the overall quality of the structure. [3D185].

SMEs would incentivize solvers to produce and demonstrate these algorithms to spur development, even if they were not printing their objects. The formulation team wanted to push participants to develop algorithms that could perform those translations and “have the printer print it without a lot of other work,” per Harper [3D105, see also 3D96]. This was necessary for the teams that participated in the construction phase but incentivized as a bonus for those who only participated in the virtual portion. SMEs believed nudging the virtual participants towards this kind of analysis would close the gap between modeling and the printed structure and improve their feasibility [3D87, 3D96, 3D105].

The latter would simulate the macro construction processes over time, building on the tool pathing algorithms. The SMEs’ aim with these requirements would be to evaluate the feasibility of the habitat through its construction sequence [3D106, 3D161, 2018-05-31]. Having created the tool path from the virtual model, solvers would have several pieces of information from which to conduct these analyses, including, e.g., the location of the printer over time and the volume of material required (and when) [3D87]. Solvers would model their 3D printer, its material handling, and the (temporary and permanent) structures it would build on-site during its task in their “4D model” [3D76, see also 3D121]. However, the emphasis remained on the printer’s autonomous movements [3D161].

SMEs awarded bonus points to teams who modeled these construction processes. The translation between virtual model and tool path and simulating the flow of materiel were assigned 17% of the total for level 2 of the Virtual Construction Competition [3D32, 3D76, 3D121, 3D200].

C.6.2.3 Outcomes of the Virtual Construction Competition

SMEs praised both the participation in and solutions from this competition, in contrast to the previous competition on habitat design. A relatively high number of teams participated in both levels of the Virtual Construction Competition. Furthermore, SMEs thought the concepts presented were “realistic” and “novel,” per reports after the competition [3D73]. The competition awarded the entire prize pot for each level ($100k)–the winners took home $21k and $34k for levels 1 and 2, respectively. After Phase 3, teams from the Virtual Construction Competition (who also participated in the Construction Competition) began partnerships with NASA teams to design additively constructed infrastructure. These partnerships were, collectively, valued in the millions of dollars.

Feedback from (Potential) Solvers Before they Submitted Solutions SMEs received multiple questions on the pressure-retaining function of the habitat’s structure. Using an inflatable bladder to contain the crew’s atmosphere is a common concept for Mars habitats: these appear in NASA’s trade studies and even in sci-fi depictions of habitats [3D93, 3D87]. Considering the available literature and work already done on this concept, some solvers considered this a “very practical route,” as relayed by the formulation team [3D87, 3D93]. Here, solvers wrote in asking if they could use inflatable structures despite the stated rules [2018-01-04]. Several SMEs even stated that it was a feasible option: Quinn, for example, thought, “there’s nothing wrong with it. It’s a really high utility idea if you’re looking at advanced concepts” [3D93, see also 3D92, 3D87].

However, this did not line up with the intent of the challenge. Solvers would not be (designing systems to) print pressure-retaining objects and structures by incorporating these inflatable structures in their designs. Instead, they would transfer the pressure retention function to another part of the habitat. This is not what SMEs wanted. Contemporaneous documents show SMEs being aware of the tension faced by solvers; they even acknowledge that it would be difficult to do with the polymer feedstocks that KSC was most interested in [3D81, 3D92, 2018-07-19, 2018-08-02]. SMEs knew this was unconventional and hard [3D88, 3D93, 3D107] but decided to stick with their decision. Per contemporaneous emails between formulation team members: “There’s nothing inherently wrong with [that] approach in a broader sense, but the intent of the competition is to 3D print a pressure-retaining structure” [3D92].

To make their intent clear, SMEs explicitly discouraged concepts that relied on inflatables to perform the pressure-retaining function. They expressed this in messages to teams and public FAQ documents [3D161, 2017-12-20, 2018-01-04, 2018-04-11]. In recalling these interactions between solvers and the formulation team, Quinn summarized it as follows:

> So, we really emphasized that in the rules to try to drive people away from using inflatables. And try to maintain that consistently throughout the competition because we would get questions about inflatables from teams. I remember we put out a couple of FAQs about it. Just emphasizing that the intention of the competition is to 3D print a pressure-retaining structure and that that is the definition of this challenge. [3D93]

Reflections on Solutions The formulation team was pleased with the quality of solutions in this competition. In particular, SMEs recognized and praised the increased fidelity of these solutions compared to those in the Design Competition—and credited the rules for driving solvers towards these details. The increased fidelity allowed them to better assess the designs (specifically their layouts) and label designs as novel when merited [3D73, 3D87, 3D106]. Along these lines, SMEs reported that “the level of detail required as part of the BIM competition ensured that proposed habitats were realistic in design, materials, and construction and able to be manufactured with [additive manufacturing] technologies” [3D73]. Furthermore, members of the 3DPH Challenge team expressed, yet again, how impressed they were with the quality of the visual products and commended how it helped them communicate their plans within NASA and to the general public. Billie described his view of the Virtual Construction Competition solutions as follows:

> NASA got huge infusion out of [the] Virtual [Construction Competition]. Those images and videos that came out of that, that’s all over NASA websites and

> NASA space [outreach]. If you have a Zoom meeting with [some NASA SMEs on the formulation team], you'll see the images in their background. So, the visual quality, the engagement of the general public, and— [getting the public to think:] "I want to go live on… Look at that cool building. I can live in that?" I think was huge. [3D225]

Despite this quality, there was one area where some solutions fell short. Some teams did not follow the SMEs' intended design exploration, both levels 1 and 2. In level 1, some teams presented submissions where the printed object did not function as the main pressure vessel, despite the rules to the contrary [3D76]. Instead, they submitted a design that relied on an inflatable structure: they were to "print a 'habitat' which is a sealed structure – not printing a "shell" which is only protection, not a sealed habitat," per formulation team meeting minutes [2018-08-02, see also 3D92]. Formulation team members summarized the solvers' thinking here as follows: solvers thought, "we can't really 3D print at scale, we know we can't make it air and watertight, and we know that there's perchlorates in the soil, and we don't know how harmful they are. … So it's not viable" [3D87]. Though SMEs thought these designs could be feasible, they believed these did not push additive construction technology forward. Per their emails, solutions that use inflatables "do not address in-situ 3D-printed construction challenges such as sealing penetrations in a printed structure" [3D92].

Solvers using inflatables in their designs was of "significant" concern for the judges and the SMEs [2018-08-02]. Their meeting minutes captured how they believed teams were skirting the challenges of pressure retention in 3D printed structures: "All the pressurized parts are brought from Earth so [the teams] don't have to deal with sealing and such with printing" [2018-07-12]. SMEs, quoting Quinn and Billie here, also stated how this design "really wasn't what we were looking for for this competition" [3D93], and how they were "kind of stuck judging that. It isn't really what we wanted" [3D88].

SMEs issued penalties and clarifications to avoid this going forward. Per Quinn: "We really emphasized that in the rules to try to drive people away from using inflatables" [3D93]. Teams that presented inflatable structures would only be eligible for half the Robustness points for level 1 [2018-07-12, 2018-07-17]. To counter these designs in level 2, SMEs also issued additional clarifications. SMEs communicated to solvers that "teams that relied on pressure retaining structures not designed to be constructed using 3D-printed materials were judged to be not as robust as those that used this construction method" [2018-11-15]. Further, to avoid large structures that would contain all of the habitat's pressure, they specified that any "membrane" used to improve the sealing properties of the teams' structure "must be autonomously placed and make up less than 2% of the structure by volume" [3D161].

Reflections on Participation Once again, the formulation team succeeded in attracting (relatively) many participants from non-space backgrounds. The formulation team's strategy to "try to show that the barrier to entry [to the Virtual Construction competition] is low and to get more participants" seemingly paid off [2018-02-08]. Around 18 teams[30] submitted entries to the first level and 11 in the second [3D127]. Like Phase 1, and in contrast to Phase 2, there was a (more or less) equal spread of academic, industry, and unaffiliated teams [3D127]. The latter were hobbyists, experts in design, architecture, and BIM who participated because of overlapping interests [3D202]. Here, one participant—an architect with an amateur interest in space–described why they decided to participate:

> I was familiar with the first phase and thought it was really impressive. And the second phase. But the third phase, being focused on BIM as a platform, really sat squarely in my interests and career focus. And put that on the backdrop of "I'm really interested in space." I would be dreaming of how to build Martian habitats regardless of the competition, so being able to put this to practical use has been really cool. [3D203]

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[30] Available documentation differs in how many teams submitted solutions: CCP's contemporaneous documents mention 18 [CCP173, CCP174], 3DPH Challenge summary documents mention 16 [3D127] or 18 [3D69], and documents from SMEs mention 17 [3D201].

Partnerships Resulting from the Virtual Competition Two NASA collaborations resulted from the work that solvers conducted in this competition. While the scope of their work covered more than the architectural design themes dealt with in the Virtual Construction competition[31], I will emphasize those below.

The first was between the winner (of the Virtual Construction Competition level 2) and an MSFC team working on new printing system concepts for the moon [LE3, 3D159, 3D215]. In the Moon-to-Mars Planetary Autonomous Construction Technology (MMPACT) partnership, the solver team would develop additive construction architectural concepts like in this competition [3D186]. The partnership's press releases described their vision as "a 3D-printed, sustainable lunar habitat that will be capable of protecting inhabitants from exposure to radiation, extreme temperature differentials, and the constant pelting of micrometeors" [3D186]. Per an MMPACT team member (and an SME on the formulation team)[32]: "SEARCH is on our team now as well, and they're doing a great job in coming up with architectural concepts to print." NASA and the Department of Defense awarded the partnership approximately \$14.55M; the architectural concept portion was a small part of this amount [3D135].

The second collaboration was between a KSC team and a participant in the Virtual Construction Competition (and winner of the final level of the Construction Competition). Like their MSFC counterparts, the former also worked on printing systems for the lunar surface [3D155]. In the REACT project, part of their intent was to develop an architectural concept: an additive constructed, unpressurized radiation shelter for the moon [3D185]. NASA awarded the partnership approximately \$627k; the architectural concept portion was a small part of this amount [3D213, 3D214].

The NASA teams felt that a closer relationship with the solver team benefitted their work. SMEs felt like they could better engage and coordinate work from these

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[31] Both partnerships described below also set out to develop and test relevant technologies for the lunar surface [3D154, 3D155, 3D159, 3D172, 3D215]; I return to these in the C.6.3.4.

[32] Reference withheld to maintain interviewee's anonymity.

outsiders in this way [3D160]. Here is how one of REACT's team members described their view of the partnership[33]:

> They're an architecture firm. We're not. We're not architects. We do have some architects, but not very many. How can you say that you're going to develop infrastructure in a lunar settlement without the help of architects to actually design it? It doesn't make sense. It's not correct. … Let's try to focus [the solver's] architectural capabilities and structural engineering firm support in a direction that will support a NASA mission objective, which is that anti-radiation protection.

C.6.3 The Construction Competition

C.6.3.1 Establishing the Construction Competition

In Phase 3, SMEs emphasized the technical areas that had not been challenged in previous phases. Specifically, the robotic architecture required to print large structures and autonomous capabilities to go along with them had not received the same attention in the previous phases. Here, SMEs decided to pivot away from materials: there had been significant developments in materials in Phase 2 and the lack of demonstrated performance in the other areas.

Instead, the Construction Competition would challenge participants to design and demonstrate large-scale, autonomous 3D printing [3D69, 3D76, 3D103, 3D108]. NASA needed systems that could print objects on the scale of a small house: the order of magnitude of the structures they envisioned building on other planets [3D34, 3D103]. Since the start, SMEs had always wanted solvers in the 3DPH Challenge to demonstrate this capability [3D2, 3D6, 3D11, 3D12]. The formulation team expected this task to be the most expensive and intensive of all, so it became the challenge's finale, with the biggest purse [3D11, 3D81].

To push solvers in that direction, the scale of objects and the degree of autonomy would ramp up in this competition. While the Structural Member Competition's objects were, at most, desktop-sized (about 1 m^2), the Construction Competition's

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[33] Reference withheld to maintain interviewee's anonymity.

objects would increase towards full scale (about 100 m^2) [3D96]. Similarly, previous phases had not required any in-depth explanation of the autonomy of their systems (like Phase 1) [3D17] or only operated over a short time printing a simple shape (Phase 2) [3D23]. Instead, Phase 3 would strongly emphasize the solutions' autonomous performance in printing something complex and at scale [3D76].

The Construction Competition followed suit with the shift towards the construction industry in the previous phase. First, the 3DPH Challenge team made a concerted effort to promote the 3DPH Challenge to the construction community. Here, they were a highlighted guest or keynote speaker at several large, construction-centric conferences [2017-07-13, 3D108, CCP103, CCP124, CCP126, CCP132]. "Anyone who's anyone in the construction industry [would] be at [these] conference[s]," per a CCP team member [3D116]. They received significant interest at these conferences, and per summaries, "the feedback from the attendees were extremely positive" [CCP154, see also CCP152]. Note that this outreach happened in addition to the outreach through the CCP's regular channels and public webinars [3D116].

Second, the construction industry SMEs that had played a role in shaping the rules for Phase 2 took on a more prominent role in this formulation process. They influenced the kinds of tests that they would require solvers' systems to perform, the metrics they would use to judge the solutions, and the relaxing of the space-focused rules of Phase 2 [2017-06-15, 2017-06-22, 2019-01-31, 3D88, 3D105]. This way, these construction SMEs strongly shaped the challenge, making it more attractive and familiar to their industry [2017-06-22].

C.6.3.2 Formulating the Construction Competition's Problem(s)

Deliverables: Printing large structures The deliverables for this final competition would be large, printed objects[34]. Drawing on their experience with ACME and

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[34] Recall that solvers who participated in the Construction competition would also need to participate in the Virtual Construction competition [3D96], increasing their workload significantly [3D98].

other associated robotics projects, the SMEs were convinced that existing, small-scale printing demonstrations (including those in Phase 2) would not address the technical challenges they were facing [3D80, 3D96]. If solvers printed the size of structures that the SMEs were interested in, it would increase the relevance of the incoming solutions to the SME's work [3D94]. Even early on, the challenge team felt they "had to establish some minimum amount of square footage volume to make sure competitors wouldn't create a system that we couldn't use," per Riley [3D11]. Similarly, Jude described the uncertainties in extrapolating from the "desktop scale":

> How does this scaling up of this portion work? How can we scale it up? You have a whole different range of problems when you scale up than you do when you are printing at a little desktop scale. How can we control this system so that we get a good print? [3D185]

Increasing the size of the printed object(s) meant solvers would need to overcome the related technical hurdles. SMEs wanted to see various designs that could print habitat-sized objects to understand what systems might work and what might not [3D36]. Note that the performance of solvers' printers from printing small, desktop-sized printers in Phase 2 would not (convincingly) demonstrate their ability to print much larger structures[35]. Exploring, and then downselecting from, the solvers' new designs for Phase 3 would be a meaningful step forward for this system's development [3D27, 3D36, 3D89, 3D94]. As such, the SMEs required large-scale prints, pushing solvers to design and develop the printing systems needed to address NASA's need.

However, despite the importance and relevance of printing large structures, solvers would not be required to print to the size required for a Martian mission. Initially, SMEs envisioned the last deliverable (of the 3DPH Challenge) to be a full-scale print of the habitat [3D11, 3D12]. Specifically, solvers would print 1000 ft^2 spaces based on the requirements for crew space laid out early in the formulation process [3D4].

The vision persisted well into the formulation of Phase 3 until it was questioned

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[35] The Virtual Construction Competition incentivized solvers to tackle some of this modeling task [3D89].

for its practicality and scaled-down. Here, the construction industry SMEs, joined by some NASA SMEs, raised concerns about the resources required to produce these structures. Specifically, the costs of construction (e.g., material, power, time) would—in their minds—exceed what solvers would be willing to spend for the challenge [3D80, 3D94, 3D96]. Some on the formulation team even questioned the need for the full-scale requirement, wondering whether the technology required for a smaller-scale print could successfully complete the full-scale one [2017-08-31, 3D81]. Additionally, Caterpillar—reprising its role as the site for the final level of the competition—was concerned about the logistics of several teams needing to build and demolish the equivalent of a "small three-bedroom house" [3D94, 2017-08-31]. Instead, the SMEs settled on a minimum area of 10.33 m^2 (or 111 ft^2), down from the full-scale design of 93 m^2 (or 1000 ft^2) [3D76]. Ash summarized the decision as follows:

> At the beginning, we said 1000 ft^2 because that's about the size of a small home. And then we realized the logistics of having a competition with that much material, and that size of a structure was prohibitive in cost for the competitors and in logistics for us and Caterpillar. So, we went down to a third scale. So much smaller, about 200 ft^2 [*sic*] total [3D103].

Nevertheless, the object's size would still make the Construction Competition a "high-risk technology development opportunity," per Quinn [3D36], even with the scaling. Printing on-site at Caterpillar—with its limited accessibility to outsiders—meant that solvers would need to complete their objects within the competition's window at their facility. Thus, the challenge solvers faced was printing their large structures quickly, requiring printers with high material deposition rates. To put this in context, SMEs had only just attained acceptable deposition rates of their printer to produce—and model the production of—comparably large structures in the ACME project [3D65, 3D89, 3D180]. Per Quinn, it was *this* requirement that made the competition more challenging than any phase before it:

> Ademir: … What is it that makes [the Construction Competition] difficult?

> Quinn: It’s the deposition rate— The amount of material that you have to be able to put out during the time frame to actually reach the square footage that we dictated. It’s also that there is not a lot of room for margin of error. You have 30 hours, so you don’t have a lot of time. [3D81]

Deliverables: What solvers would print The printed objects within the Construction Competition would progress from small structures to large and more complex ones across its three levels. Participants would be required to print bigger and more intricate/complex structures [3D76, 2017-07-13, 2017-07-20, 3D120]. Much like the Structural Member competition in Phase 2, SMEs chose these with particular performance tests in mind (explained in the section C.6.3.2 below). First, in level 1, solvers were to print a 6 m^2 horizontal slab (with a wall interface), simulating a slab on grade foundation for a building [3D76, 3D120, 3D88]. Solvers would also need to print test specimens to test their printed material’s characteristics on the same scale as those used in Phase 2. Next, in level 2, solvers printed a large cylinder–approximately 3 m^2 by 1.5 m, including a larger foundation [3D76]. This structure, referred to as a “bucket” [2018-12-13, 3D88, 3D120], would simulate a (hydrostatic) pressure vessel. Finally, in level 3, solvers would print their designs[36] for their habitats at a third scale, with the minimum area described earlier [3D76, 3D120].

Autonomy The autonomy of the printer was the most important criterion in the Construction competition—"the biggest focus of Phase 3” per a member of the CCP team [3D29, see also 3D80]. Similarly, while the goal of minimizing human intervention in the printing process had been a part of every competition in this series [3D122], this time, “we really wanted to push the autonomy,” per Harper [3D96]. To emphasize this importance to solvers, SMEs awarded over 40% of the available points to the

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[36] Because of scaling, certain features of the full-scale designs would not fully reflect the habitat. SMEs understood and were ok with some inconsistencies between scales as long as the simplifications were acceptable [2018-04-05]. For example, smaller penetrations might fell outside of the print resolution. Per Billie, teams were “supposed to print the structural or pressure retaining components. And since it’s a 1/3 scale, they can leave out the small penetrations, but they need to include the bigger ones” [3D88].

printer's autonomous behavior in each level, far surpassing other areas like materials or strength [3D76]. As relayed by Harper, SMEs firmly believed that its importance should be communicated with the scoring distribution "because teams are going to go after the maximum points" [3D96].

Why this emphasis? NASA highly values the ability to pre-deploy these structures: considering the risks of being on the surface of Mars, any such structure would, ideally, be waiting for astronauts to inhabit as soon as they land [3D124, 3D29, 3D81]. Communication delays with that planet would mean that the printers would need to operate (mostly) autonomously [3D103, 3D94]. Even if pre-deployment is too high a bar, high levels of autonomy would "massively" reduce the risks associated with construction for astronauts [3D80, see also 3D94].

Throughout the Phase 3 formulation process, there were discussions into how high the bar for autonomy would be set in the challenge. Early drafts considered perfect autonomy, in line with the ideal for a Mars mission. Summarizing the formulation team's discussions, Harper stated they would have loved to see solvers demonstrate this performance: teams would "come in, push the button, and walk away for the day. And print [their] structure. That would be the ideal." [3D96, see also 3D105]. But they knew that requiring solvers to perform to this bar (and no lower) would be too stringent. First, SMEs like Quinn and Ash believed it would be too difficult and too costly for the solvers to achieve this: this would be "a very tall challenge" [3D81], as autonomous systems are "very hard and very expensive" [3D103, see also 3D6, 3D80]. Second, SMEs also believed that a stringent requirement for autonomy would not make for a worthwhile competition [3D105]. If solvers were eliminated after their first failure, it was likely that no one would finish. Ash described how the formulation team "didn't want them to put all that time and effort in, come to Peoria, and get knocked out in the first two minutes because they had to do a manual intervention." [3D103].

With zero interventions remaining the ideal, the rules would penalize solvers whenever they interacted with their printer. Specifically, when they touched their robot to resume printing, it would result in more severe penalties than when they did not—termed physical and remote interventions, respectively. Harper and Ash explained these differences as follows. In the former, teams would "have to go out there with a shovel or hammer or wrench and adjust something" [3D105, see also 3D81]. In the latter, teams may have to "change a variable, or reboot the computer, [or] do a software adjustment" [3D103]. While both interventions were unwanted, SMEs deducted more points for physical interventions: requiring remote interventions might reduce the printer's efficiency, but physical ones would pose severe problems on Mars [3D103, 3D105].

Printed material characterization By deemphasizing materials, SMEs changed their importance in this competition. First, materials took a backseat: as described above, SMEs shifted the attention from materials to autonomy with an updated points distribution. In the Structural Member Competition, many points depended on material selection. In contrast, less than 10% of the total points in the Construction competition were available for material selection [3D76]. Note that Phase 2's scale for material scoring—described in C.5.2.2—carried over to the Construction competition. The scale (yet again) served as a guide to show solvers what kinds of material NASA preferred and to score solvers' submissions.

Second, SMEs also lightened the burden associated with materials. They believed developing a new feedstock, printing larger objects, *and* demonstrating high levels of autonomy within one competition "would have been too much" [3D80, see also 3D92, 3D103]. In response, SMEs removed the requirement for a minimum ratio of aggregate to binder in feedstocks, removed the heavy penalties on imported materials and water, and allowed previously discouraged, non-optimal materials–specifically Portland cement—to be used [3D25, 3D81, 3D92, 3D93, 3D101].

SMEs believed that these changes would give solvers the leeway to ignore this category if they found it too onerous to comply. Per their conversations at the time, SMEs understood that the rules for Phase 3 "(probably) [wouldn't] do anything to advance state of the art in terms of materials" [3D92]. But they believed that relaxing these rules on materials would give solvers room to focus their efforts elsewhere [3D81, 3D93]. Quinn recalled how the formulation team thought about this tradeoff: "I think that was the overarching rationale was [as follows]: 'even if we don't have teams developing new cementitious materials, they can make technology advancements in other areas'" [3D80].

The deemphasis also changed what kinds of material characteristics SMEs would look for. Less emphasis would be placed on materials generally, but the attention would also shift from the feedstock's recipe to its printed behavior. Quinn described the shift in focus as follows: "It's really just, like, looking less at what material might people use and more about what we are actually worried about. What would we want to see in terms of performance of materials in the application of the habitat" [3D93]. For the feedstock's structural performance, SMEs characterized the printed structure's ability to retain pressure as well as its surface properties. For the feedstock's environmental performance, SMEs revisited the Martian conditions that would affect the printed structure. However, despite extensive knowledge of what the habitats—and their inhabitants—would go through on Mars, they decided to limit the tests to two: micrometeorite impacts and extreme temperature cycles. I explain the structural and environmental performance characteristics below; they are discussed per their share of the score in the Construction Competition.

Structural performance: Pressure retention Across both competitions in Phase 3, SMEs wanted to drive the printed structures to retain pressure. The Construction Competition operationalized this in two ways: printing a hermetically sealed structure and creating preplanned penetrations in a printed surface (instead of relying on rework) [3D189, 2017-07-14]. SMEs hoped solvers would demonstrate these with their printers and not (overly) rely on prefabricated parts [3D105]. In this vein, inflatables would not be allowed [3D87, 3D76]—much like the Virtual Construction competition. However, autonomously installing smaller elements to incorporate the penetrations or applying a sealant coating onto the structure's printed surface would be acceptable [2018-01-11]. SMEs believed that demonstrating these abilities would be "challenging," as they depended heavily on the material and how well each layer bonded to the others [3D88]. Success would mean a significant gain for the field of additive construction [3D80, 3D81]. Per Quinn:

> [We emphasized] that the intention of the competition is to 3D print a pressure-retaining structure and that that is the definition of this challenge. . . . We also really wanted to draw people to seal penetrations because that was seen as something that would really advance the state-of-the-art for 3D printing for construction. [3D93]

Solvers would demonstrate their pressure retaining capabilities across two levels in the Construction competition. The formulation team found tests that approximated the desired behavior instead of ones that would more accurately reflect the use case of the habitat [3D108, 3D165, 3D189, 2017-08-03]. This decision came down to safety: the construction industry had long used these kinds of tests in cases when failure of the vessel was a possibility, and the formulation team would employ that same thinking here. As one of the construction industry SMEs, Blake described the risk as follows: "You don't want to use compressed gasses, 'cause they're really bad when things go wrong" [3D88].

Solvers would try to avoid leakage between deposited layers and leakage around their penetrations in both levels. In level 2, SMEs tasked solvers with printing the "bucket" and filling it with water. Its pressure-retaining performance would be measured by the structure's leakage rate [3D76]. In level 3, SMEs would deploy a smoke bomb inside the printed scaled models and deduct points for any escaping smoke [3D76]. Across levels 2 and 3, the points available for this performance were less than 13% of the total.

Structural performance: Surface properties SMEs also imposed tests on the printed structures' surface properties, specifically how flat and level their prints could be. Much like the tolerance requirements in Phase 2, SMEs wanted to measure the different printing systems' accuracy. Specifically, measures for flatness and levelness—derived from measures for concrete–would verify that their foundation could function as intended: a slab with a slope of zero and minimal elevation changes across its surface. Here, SMEs decided to relax the Phase 2 tolerance criteria. SMEs did not prescribe a tolerance band for the slab, assigning a zero score to solutions that could not meet that [3D88]. Instead, more points were deducted for greater deviations from the ideal [3D76]. The scale would award more points for smaller depressions and slope to "measure the quality of how you print," per Billie [3D88]. For the slab-on-grade structure in level 1, the total amount of points available for flatness and levelness were 7% and 2%, respectively [3D76].

Structural performance: Material Strength Lastly, to provide a basic picture of the materials' characteristics, SMEs incorporated the material strength tests from Phase 2. Specifically, solvers would print pre-specified test samples, which would be subjected to compressive and bending loads. The level 1 rules instructed teams to, once again, perform their compression testing through a third-party lab using the standard ASTM C39 test. However, the beam bending test would be performed on-site at the level 3 face-off. Both tests retained their tolerance requirement from Phase 2. Total points available for these tests—related to the forces they could withstand without failing—did not exceed 9% of the available points per level, with an additional 0.5% awarded for complying with the tolerance requirements (in level 1).

Environmental performance: Impact resistance Micrometeorite impacts are a significant factor for large structures on Mars. Mars' thin atmosphere means that (some) objects do not burn up upon entry like on Earth. As such, their high kinetic energy could seriously damage the habitat. NASA SMEs have studied these impacts, particularly their role in habitat design [3D32, 3D80]. As a result, NASA has some information on the meteorite flux, energy, and various materials' resistance to impact [3D92, 3D93 3D185]. In this vein, the ACME project had made strides in testing how well different 3D printable concrete mixes could withstand hypervelocity impacts [3D204, 3D63]. "But that's still a long way to go," per Blake, who was also a member of that project [3D89].

Because of its potential to harm the habitat, SMEs wanted to incorporate this criterion in Phase 3. However, achieving realistic speeds with comparable objects requires highly specialized equipment and testing facilities—in this case, NASA's hypervelocity testing lab at its White Sands Test Facility [3D93, 3D204]. As such, performing these tests is expensive and, per SMEs, also an undue burden on solvers in the 3DPH Challenge [3D80]. Like testing materials in a vacuum, Quinn again believed that this was their responsibility, something that NASA would have to take on "if you were actually going to fly the material" [3D93, 3D226].

Instead of the standard impact tests, SMEs turned to drop tests. Here, prespecified weights would be dropped from prespecified heights onto the printed structures in levels 1 and 3 [3D108, 3D121], removing the need for specialized equipment. SMEs would measure the performance of the solvers' structures by how well they withstood multiple impacts, i.e., how the weight cracked, deformed, or perforated the structure [3D76]. The points available for the submission's impact performance in levels 1 and 3 were 9% and 5% of the total, respectively.

Environmental performance: Extreme temperature cycles Temperatures on Mars can swing from 20 °C to -125 °C [3D192], placing significant strains on objects on the surface. Through this range of freezing and thawing[37], a printed habitat could expand and contract quite severely depending on the material(s) used—determined by the material's coefficient of thermal expansion [3D73]. Cycles of expansion and contraction could cause damage to the habitat or worsen existing thermal stresses left by printing. In the vein of focusing on the material's performance as a building material for a habitat over its composition (as described in Printed material characterization). Quinn summarized their decision as follows:

> [We had] high-level philosophical discussions on what does a habitat have to do. So, one of the things that it has to do is withstand temperature swings and freeze/thaw cycles. So, we decided to put that one in there. [3D93]

Unlike the impact test, some facilities could subject test specimens to the relevant conditions. Here, the formulation team drew on a standardized test in the construction industry [3D105]: the ASTM C666 test subjected test specimens to freezing and thawing cycles [3D76, 3D92]. Much like in Phase 2, SMEs reasoned that the costs of solving could be reduced by leveraging non-space, third-part labs that could test for the relevant parameter [3D102]. Quinn summarized this decision as well:

> [ASTM C666]'s viewed as a more accessible test. It's commonly done in construction. So, we felt like that one, teams would have access to a test lab here to actually execute that test and that the cost of that wouldn't be prohibitive [3D79, see also 3D93].

But the SMEs traded the ease of solving for the utility of the result. Much like the ASTM tests conducted in Phase 2, this standard test was also formulated for the performance of cement. Quinn, like others, believed that the differences between polymer-based feedstocks and the cement-based ones meant that the freeze/thaw test "[wasn't] necessarily the most appropriate test" [3D101, see also 3D73, 3D93]. The

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[37] Abbreviated as "freeze/thaw" [2017-10-12].

testing labs that solvers approached reported that they “don’t even know how to run a freeze/thaw test on [a] mostly plastic-based material. And if [we] do run it, it’s just going to break” [3D92].

In the end, the competition dynamics won out, and solvers would only perform one test. Some SMEs on the formulation team wished to have tests tailored to specific material families [3D101], even suggesting alternatives to use alongside the ASTM C666 test [3D92]. Nevertheless, it was more important to judge all submissions equally to them. In their contemporaneous emails, SMEs expressly stated that they “don’t really want to open the door to having to make case-specific decisions on standards and scoring for every team” [3D92]. The ASTM C666 test would be a best-fit across the material tests, and straightforwardly, higher performance would result in a higher score for this criteria. Billie described their thought process as follows:

> Some of the materials that were developed, especially in Phase 3, are not conducive to standard tests. [It’s a double-edged sword:] you want standard tests, so you don’t want to make up tests to match the materials. But if the material doesn’t match the standard tests, you say [to the solvers:] “do the best you can, and we’ll figure out what your score is.” [3D88]

Across levels 1, 2, and 3, SMEs assigned no more than 9% of the total per level for this performance (it decreased to 5% in level 3).

Environmental performance: Material safety Any material used to build habitats for the crew will need to be safe to be around. In the space context, material safety comprises three factors: flammability, toxicity, and its ability to block radiation [3D80, 3D11, 3D185]. All three are crucial for the crew’s survival [3D79, 3D32]. But none were included in the Construction competition. Quinn described how “they are tests that are very difficult [to] execute, . . . really expensive, and a lot of test labs that are accessible to teams wouldn’t have the capability to do these tests” [3D79]. As such, they made cuts to tests related to material safety, aiming to make it easier (and less costly) to participate. Because of the expense and the uniqueness of these performance levels, NASA would retain the burden of addressing these criteria in a follow-on development [3D80]. Quinn again explained their view of whose responsibility these criteria were:

> This is a public-facing competition, so you can't necessarily load it up with these highly specialized requirements. If we decided to move forward with a specific habitat design or specific material, that's something that NASA would do on our side. [3D93]

Flammability and toxicity NASA has strict requirements for testing materials that could be flammable or toxic in a crewed environment. Per Quinn, "every material that flies to space has to undergo both of those tests" [3D79]. These are of particular concern with new materials, such as those created for (and processed by) 3D printing [3D93, 3D101]—for example, some teams are concerned about off-gassing of volatile organic compounds and nanoparticles [3D185]. SMEs described how they tried to incorporate these criteria [3D93, 2017-07-20]. Quinn even wished they had a bigger budget to perform "flammability testing of the teams' material, or toxicity testing, or vacuum outgassing testing" on the incoming solutions [3D101]. But, as Harper described, "in the end, we just all agreed that the value doesn't justify the expense" on the solvers' side [3D105].

There were several arguments against including them. First, these characteristics are tested to levels that are highly specific to the space industry [3D93, 3D101]. While the formulation team tried to find equivalents, they could not find other labs that would test these effectively, requiring specialized tests and facilities. Subjecting solutions to the more commonly available ones would be a waste of resources [3D105]. Second, running these tests at NASA is expensive and difficult to access, even for NASA SMEs (these performance characteristics are also tested at the White Sands testing facility) [3D101, 3D93, 3D95]. And lastly, SMEs could reevaluate and modify the materials at a later time. For example, SMEs thought they could add something to the feedstock later to ensure that it better complied with the flammability requirements [3D80].

For example, Quinn described their nominal reevaluation process of a material they thought was promising for a space application:

> This [material] looks good for this application, but this has no flight history. So here are the things we have to do to evaluate it. And sometimes that informs, "well, it's flammable, can we add flame retardants to it? Can the material developer tweak the formulation somehow to meet our needs?" So, it kind of starts that interchange in some way. [3D80]

Radiation SMEs revisited the radiation requirements for feedstocks in the Construction competition. Recall that a material's ability to absorb and withstand the radiation environment on Mars is crucial to providing a safe habitat for the crew. There were initial conversations about including these kinds of requirements, thus asking solvers to provide these analyses [3D6, 3D11, 3D92]. But despite its importance, SMEs decided not to define the radiative environment in the rules. As such, they did not require solvers to take these into account in their solutions[38] [3D92, 3D93, 2018-03-29]. SMEs believed that that teams were "already doing a lot" [3D226], and that this would be too limiting [3D11]. Additionally, the uncertainty did not need to (only) be addressed by the materials: the specific shape and geometry of the habitat could take this into account [3D6, 3D92, 3D93], and the printed structure could be modified to reduce the radiation flux (through, e.g., inflatables or coatings) [3D11]. The material's ability to withstand radiation did not need to be solved in the challenge: like the other material safety criteria, Quinn stated that if a material "was actually going to be infused in the mission, [radiation testing] would be something that NASA and the [material] partner would do together to fly it" [3D93].

C.6.3.3 Printer Form Factor

Lastly, SMEs maintained their stance against printer designs that used a powder bed. Their reason stayed the same: they wanted to "discourage use of powder-based

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[38] Note that, like in Phase 2, the material scoring table's preference for polymer binders also partly reflected their utility to protect against radiation [3D11].

system[s]" because of the dangers it would pose, both in a microgravity environment [3D92, see also 3D89] and also at the Caterpillar facility where the final round was held [3D226]. In this case, SMEs assigned points to the suitability of the solvers' printers to the space environment—the more suitable the SMEs judged that the systems were to the Martian surface, the higher number of points they would get. In total, SMEs dedicated up to 1% of total points available for level 1 to the printer's suitability for a microgravity environment[39] [3D76].

C.6.3.4 Outcomes of the Construction Competition

The Construction Competition was another big success. While the participation in this competition was equally as low as Phase 2, the solutions presented SMEs with important insights into the printing processes for different materials. Like the Virtual Construction Competition, SMEs awarded the total prize pot ($1,120M) at each level of this competition—the winners took home $55k, $105k, and $500k, for levels 1 through 3, respectively. NASA teams experimented on feedstocks from two teams, further characterizing their in-space performance. And teams from the Construction Competition formed partnerships with NASA teams to design, test, and use additive construction systems for NASA's aims. These partnerships were, collectively, valued in the millions of dollars.

Reflections on Participation Like the Structural Member Competition, participation in this hardware-intensive competition was relatively low. This time, seven teams submitted an entry across the competition's three levels, with only two reaching the final head-to-head [3D127]. Once again, all seven teams stemmed from industry or academia, three and four teams, respectively. Not one non-affiliated team managed to submit a solution. The cause of the low turnout was likely the cost and effort of creating a viable solution yet again. In a survey of participants, several respondents

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[39] The printer's footprint and size were scored together with the microgravity suitability requirement.

who did not finish their Phase 3 solutions blamed a lack of resources or the amount of work for their lack of progress [3D98]. For example, when asked why they did not complete the phase, one participant responded, “Budgetary constraints in development” [3D98]. Similarly, teams communicated their concerns about the costs of participating, specifically in the final level. As Quinn described: “And [the final level] was something that we got pushback on, even from some of the teams. Saying ‘it’s really expensive, it’s really cumbersome for me to come and afford all this to a head-to-head event’ ” [3D101].

Similarly, few teams had space industry experience before participating in the Construction Competition [3D55, 3D56, 3D216]. Instead, they came from architecture, civil engineering, and additive manufacturing backgrounds [3D164, 3D165, 3D217, 3D218, 3D219]. However, some teams had participated in previous phases, and by this point in the competition, had started to gain a foothold in the space industry: designing similar systems, establishing a presence, as well as winning other contracts in this industry [3D99, 3D133, CCP71, P3]. NASA personnel observing the 3DPH Challenge expressed their surprise at the evolution of some of the teams: “Those people in Phase 1, I would never have thought [they] would get to Phase 3” [3D100].

Reflections on Solutions

Solvers’ materials While SMEs accepted that the rules surrounding materials needed to be relaxed to increase participation, not all were happy with this change. In the Construction Competition, solvers were more able to explore material families and combinations within their capabilities, resources, and goals [3D101]. But some SMEs, like Quinn, felt that the (newly expanded) allowable tradespace for Phase 3 gave solvers too much leeway. In their view, solvers explored materials that were not “in the spirit of the rules” [3D101]. The hydraulic cement concretes “were extremely difficult to deal with. They’re very messy,” as Ash described [3D94]. In short, they were not feasible for planetary uses. Ash continued their thoughts on how they felt about this change:

> Some of these Portland cements concretes are not realistic for space. We don't have the material, the water, and it's a vacuum. So, I was pushing more for Mars realism. … The price we paid [when we made the changes in the rules] was that we got something that was not as good for space but pretty good for Earth. So that's the price you pay for giving [the participants] freedom. You might not get exactly what you want. [3D103]

Despite the relaxation, the solvers still produced feedstocks that SMEs thought were "novel and innovative" [3D73]. First, the winner of the final level—AI Spacefactory—developed a polymer-based feedstock where the binder, polylactic acid (PLA) plastic, could be produced on Mars. It would tie into existing NASA's synthetic biology programs to do so [3D162] and further reduce planetary construction costs [3D226]. Additional advantages included radiation shielding (per C.5.2.3), low changes in volume based on temperature (per C.6.3.2), and low hardening time [3D73]. Along with the PETG binder from Phase 2, SMEs touted it publicly as one of the polymer blends "with potential applicability" for their vision of in-space manufacturing [3D140].

Finally, two teams printed with concretes relevant to planetary environments but had to drop out of the competition. One team used a magnesium oxide cement as a feedstock, a readily available compound in lunar and Martian regolith [3D65, 3D73]. MSFC SMEs had tried this in their ACME project but were not successful. Per one of its leads[40]: "We started using [magnesium oxide cement] in the ACME project. And it's horrible. Our formulation of that is absolutely awful. But that doesn't mean that another [company] or somebody couldn't make a better formulation with the same materials." Ultimately, difficulties with implementing autonomy in their printing system and a lack of resources made it difficult for the team to continue [3D216].

Another team based their concrete on sulfur. SMEs were interested in this material for its potential as a binder—the ACME project had also investigated it previously

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[40] Reference withheld to maintain interviewee anonymity.

[3D65, 3D160]. Despite its applicability to planetary context, however, the logistics of the competition were too big a hurdle to overcome. It came down to safety: sulfur needs to be heated to flow as a binder and releases toxic fumes in the process [3D89, 3D101]. Per Blake: “Well, it’s really problematic from a safety standpoint, especially when you have large crowds. You couldn’t have them in the open area there at Peoria” [3D160]. In collaboration with Caterpillar, SMEs tried to work out a strategy to keep onlookers safe: confining the printer to a plastic tent with ventilation to the outside was one serious consideration; printing via video link was another [2019-03-21, 3D95, 3D160]. But in the end, the team decided not to participate in the final level [2019-03-28, 2019-04-03].

In both cases, SMEs had hoped these teams could have continued their development to learn from their designs. Finley “[was] hoping that Northwestern would come with their sulfur concrete, or Colorado School of Mines with their magnesium oxide. . . ” [3D82]. In our interview, Finley described the kinds of questions they would ask these teams, ranging from their feedstock design, feedstock handling just before printing, to printing and control processes [3D95]. Relatedly, several SMEs lamented that these teams had dropped out. Finley acknowledged that “it would have been a logistics nightmare [to accommodate them] down there. But it would have been really cool.” [3D95]. Likewise, Quinn commented that allowing teams to participate from their home location—something that was initially considered—could have kept these teams in the competition [3D226].

Solvers’ robotic architectures SMEs were happy to see the range of printer architectures the solvers designed. In particular, SMEs were impressed by the combinations of printers and machinery to move it around the printed object [3D73, 3D160]. Blake was “really intrigued and tickled to see the range of mobility system designs that were a function of the selected architecture. It was pretty cool” [3D89]. SMEs praised the demonstrations of these printing architectures [3D109]: they showed that previously unprintable structures might not be. Quinn described the demonstrations made by solvers as follows:

> I think, from the perspective of the actual manufacturing equipment, it really provided NASA with a good calibration of what the state-of-the-art is with these technologies, and how we can push that a little bit in terms of being able to build larger, have higher material deposition rates. [3D80]

Solution infusion into NASA projects After Phase 3, SMEs characterized two feedstocks from the Construction Competition. Samples of both the winner's and the runner-up's feedstocks will fly or have flown on-orbit. AI Spacefactory flew their PLA and basalt fiber feedstock on a United States Air Force experiment called Materials Exposure and Technology Innovation in Space (METIS) [3D80, 3D151]. PSU will fly their hydraulic-cement feedstock on Materials International Space Station Experiment (MISSE) [3D134]. In both experiments, the samples are exposed to the space environment. Here, NASA can "gain valuable data about how the materials hold up in the environment in which they will have to operate," per the co-investigator and principal investigator those payloads [3D168, see also 3D80]. And Quinn thought further characterizing these feedstocks on-orbit was another of the "really good outcomes" [3D80].

Partnerships Resulting from the Construction Competition

Developing printing infrastructure for the moon The partnerships between NASA and the 3DPH Challenge teams described in C.6.2.3 included a significant hardware component and the architectural work. SMEs from both MSFC and KSC relied on the solver teams to develop printer architectures for the lunar surface. In the MMPACT project, MSFC also partnered with ICON—a terrestrial additive construction firm that collaborated with the Colorado School of Mines in the

Construction Competition [3D186, 3D215]. Per their stated vision, ICON's task would be to develop and test new feedstocks using lunar soil simulants [3D172]. They would then use these insights to develop and "increase the technology readiness level" of key elements of the lunar printer [3D159, see also 3D172]. While ICON's participation in the 3DPH Challenge certainly raised its visibility, its maturity in its processes won over the additive construction SMEs. As one of them described[41]:

> When we were looking for a printing company counterpart for the MMPACT project, [we] listed every company in the US that was doing either printer development or structure development, and immediately ICON rose to the top. So we went and talked to them. ... I wanted somebody with a demonstrated process. I wanted somebody who wasn't just building and selling printers but was actually printing. So I knew that they understood the actual printing operations and the kinds of things that you can run into.

The REACT project has similar components. The participant team, AI Spacefactory, will work with the KSC SMEs to develop a material "that mimics lunar regolith, or dirt," per their press releases [3D154, see also 3D155]. Likewise, they will use their insights to design and test printer elements that can support this kind of material—in this case, an extruder [3D185]. In contrast to MMPACT, however, this partnership placed a stronger emphasis on testing in equivalent conditions. Specifically, the KSC SMEs described how part of their role was to convey the specifics of the lunar environment, provide these conditions in a test chamber, and help the AI Spacefactory team tailor their design to work in these conditions [3D154, 3D155, 3D185]. Per an SME on this partnership[42]:

> So, one of the responsibilities on our end is to convey what the lunar environmental conditions are so that they can tailor the design of the material and of the structure itself in a way that will be functional in the lunar conditions. ... So, we provide that insight over to them and help them modify and adjust their system so that they can perform in that environment.

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[41] Reference withheld to maintain interviewee anonymity.

[42] Reference withheld to maintain interviewee anonymity.

Printing an analog habitat Early on, the Design Competition's rules envisioned a 3D printed habitat analog where a crew could train for their stay on Mars. About five years later, this would become a reality. JSC team was planning NASA's first long-duration habitat simulation, where a crew of (simulated) astronauts would live inside a simile of a habitat for a year [3D160, 3D223]. Crew Health and Performance Exploration Analog (CHAPEA) would track their food intake and how they interacted with the space, among other factors [3D224]. Under budget and schedule pressures, the CHAPEA team investigated different options for a space that could suit their needs, including building a purpose-built one.

Here, the CHAPEA team included additive construction (of a dedicated habitat) as one of those options. The team consulted with the 3DPH Challenge team to better understand (if and) how this method could work for their needs [3D160]. These conversations were crucial in helping this method gain traction as a viable option—the CHAPEA team had not set out to use this construction method. Per a CHAPEA team member who was a part of the discussions between their team and the CCP:

> So, in talking with [the CCP lead] and her team, the first thing I realized was that this was a viable option. Because I didn't know. You can go online and read about things, but having that connection with her team made me realize that "ok, this is something realistic and feasible for us to do." [3D221]

Additive construction was the most attractive option for this project [3D221]. First, the timeframe to additively construct the required building fitted within CHAPEA's schedule. Second, ICON presented the cheaper bid—attributed to not developing the hardware needed to print the habitat and their long(er) experience in printing this size of the structure. Third, this option had the added benefit of providing another demonstration of new technology. Per the CHAPEA team member, "it was the only one that had the benefit of maturing— possibly helping to mature technology that NASA was looking for outside of Earth" [3D221]. So, NASA launched a procurement to print their analog habitat [3D157].

Additionally, one important risk would give a 3DPH Challenge participant an advantage in their bid. This structure would need to support the crew over an extended period, and their safety was paramount [3D221]. Additive construction is a new technology, and teams were still developing their printing systems while bidding on the project. In contrast, ICON had already successfully navigated their city's building codes (in Austin, TX) and had printed homes that people currently were living in [3D160]. To the CHAPEA team, this proxy for safety weighed more than the characteristics that interested the formulation team. Per the CHAPEA team member again:

> From my perspective, the functionality of how each of these companies print, or the specifics of their printer, is less important for me being able to say, "I have evidence that says if I put four people in this structure, they're going to be safe." [3D221]

References

Table C.1: Documents referenced in the "Formulating the 3DPH Challenge" Case Narrative

Reference	Date created	Description
3D1	Jul 25 2013	Agreement between NASA and DOE concerning NNMI
3D2	Mar 9 2015	First draft of 3DPH Challenge rules
3D3	Apr 3 2015	Whiteboard of Brainstorming session (Design Challenge goals)
3D4	Apr 3 2015	Whiteboard of Brainstorming session (Design Challenge rules)
3D6	Mar 30 2015	Second draft of 3DPH Challenge rules
3D7	Apr 8 2015	Revision of 3DPH Design Challenge rules
3D8	Apr 14 2015	Revision of 3DPH Design Challenge rules
3D10	May 1 2015	Revision of 3DPH Design Challenge rules
3D11	Aug 28 2017	Interview with "Riley"
3D12	Jul 25 2015	First draft of 3DPH Challenge "Level 2" rules (printing the full habitat on site)
3D13	May 7 2015	Executive summary of the Design Challenge
3D16	May 15 2015	Notice (SpaceNews) describing Design Challenge launch
3D17	May 16 2015	Final version of 3DPH Design Challenge rules

3D20	July 13 2015	First draft of 3DPH Structural Member Challenge rules (with CCP team commentary)
3D21	Apr 3 2015	Whiteboard of Brainstorming session for Structural Member Challenge
3D22	Apr 3 2015	Whiteboard of Brainstorming session for "Level 2" (printing the full habitat on site)
3D23	Apr 14 2017	Final Structural Member Challenge rules
3D24	Jul 09 2018	Questions to "Finley" via email
3D25	Jul 13 2018	Questions to "Finley" via email
3D26	Aug 21 2015	Team's descriptions of designs
3D27	Aug 24 2017	Interview with CC3
3D28	Aug 24 2017	Interview with "Ash"
3D29	Jul 16 2018	Questions to CC16 via email
3D30	Jun 26 2017	Questions to "Riley" via email
3D31	Sep 23 2016	EMPC Presentation and request for ATP for 3DPH Challenge Phase 2
3D32	Apr 4 2018	3DPH Phase 3 Webinar on Virtual Construction and BIM
3D33	N/A	Completed Technology Project: progress by the ACME project under GCD (summary)
3D34	Nov 7 2017	ACME 3D Printing Structures with ISRU-Presentation
3D35	Aug 7 2015	Brief factsheet on GCD grant for ACME
3D36	Aug 24 2017	Interview with "Quinn"
3D37	N/A	Slide describing high-level requirements for Ice Home project
3D38	Aug 17 2016	Ice Home CONOPS baseline
3D39	Dec 21 2017	Ice Home CONOPS revision 1.20
3D43	Jul 2016	Mars Ice House conference paper–Conference on Environmental Systems, ICES-2016-222
3D48	2018	Penn State Tech Summary: 3D Printing Geopolymer Structures Having a Lower Ecological Footprint ID# 2017-4699
3D55	Jul 1 2019	SDSU XHAB results summary: Development and Mechanical Properties of Basalt Fiber-Journal paper in Composites Science
3D56	May 31 2018	NASA Selects University Teams to Develop System Prototypes for Deep Space-Press release
3D63	Jul 21 2017	Additive Construction: Using In?Situ Resources on Planetary Surfaces-Presentation
3D65	Nov 1 2018	The Disruptive Technology That is Additive Construction: System Development Lessons Learned for Terrestrial and Planetary Applications-AIAA Space 2018
3D69	Oct 2018	NASA Centennial Challenge: Three Dimensional (3D) Printed Habitat, Phase 3-IAC 2018, IAC-18-E5.1.5
3D71	Feb 2014	TechPort: 3D Additive Construction with Regolith for Surface Systems-Technology Factsheet (CIF)

3D72	Apr 11 2016	NASA Centennial Challenge: Three Dimensional (3D) Printed Habitat-ASCE Earth and Space Conference 2016
3D73	Mid year 2019	Centennial Challenges Program 3D Printed Habitat Challenge Mid-Year report (FY2019)
3D76	Jun 27 2018	Final Phase 3 (Virtual Construction and Construction) rules
3D79	May 3 2019	Interview with “Quinn”
3D80	Oct 4 2019	Interview with “Quinn”
3D81	Apr 30 2019	Interview with “Quinn”
3D82	Apr 30 2019	Interview with “Finley”
3D87	May 3 2019	Interview with “Stevie”
3D88	Apr 12 2019	Interview with “Billie”
3D89	Apr 29 2019	Interview with “Blake”
3D90	May 31 2017	UAF Lawlor wins NASA prize-Press release
3D91	Jun 4 2019	Questions to “Quinn” via email
3D92	Mar 17 2020	Excerpts from relevant email traffic between SMEs on judging team
3D93	Dec 4 2019	Interview with “Quinn”
3D94	Oct 15 2019	Interview with “Ash”
3D95	Oct 25 2019	Interview with “Finley”
3D96	May 2 2019	Interview with “Harper”
3D97	May 16 2015	Reference page included with final draft of 3DPH Design Challenge rules
3D98	Oct 10 2019	CCP survey of 3DPH participants
3D99	Sep 2018	NASA Centennial Challenges Program Update-AIAA Space 2018
3D100	April 3 2019	Interview with NASA SMEs
3D101	Mar 16 2020	Interview with “Quinn”
3D102	Feb 20 2020	Interview with “Finley”
3D103	Mar 10 2020	Interview with “Ash”
3D104	Aug 24 2017	Interview with CC2
3D105	Mar 12 2020	Interview with “Harper”
3D106	April 29 2020	Interview with “Billie”
3D107	Sep 05 2018	Midterm Webinar (and review of Phase 3 to date)
3D108	Oct 25 2017	EMPC Presentation and request for ATP for 3DPH Challenge Phase 3
3D109	Feb 20 2020	Additive Manufacturing at NASA overview
3D110	July 10 2015	First draft of Structural Member Challenge rules
3D112	July 13 2017	FAQ document for Structural Member Challenge
3D115	Nov 14 2019	In-Situ Resource Utilization: Robotics and 3D printing as the Picks and Shovels of the 21st Century-Presentation
3D116	May 8 2019	Interview with CC25
3D117	May 16 2015	3DPH Challenge promo at Maker Faire 2015-YouTube video

3D118	May 16 2015	Design Challenge launch at Maker Faire 2015-YouTube video
3D119	Oct 12 2015	Design Challenge promo-YouTube video
3D120	Dec 19 2017	Informational Webinar (for Phase 3)
3D121	Apr 4 2018	3DPH Phase 3 Webinar on Virtual Construction and BIM (Transcript)
3D122	Nov 16 2016	Informational Webinar (for Phase 2)
3D124	Jun 13 2017	Mars Ice Home description-Presentation
3D125	Jun 23 2017	Interview with CC26
3D127	Mar 20 2020	CCP summary of participation and awards in all 3DPH phases
3D130	May 16 2018	Zero Launch Mass Three Dimensional Print Head-ASCE Earth and Space Conference 2018
3D133	N/A	AI Spacefactory press coverage
3D134	Sep 23 2020	Interview with “Quinn”
3D135	Oct 2 2020	NASA’s Project Olympus-Press release
3D137	Jun 21 2018	Robotics in Construction (NASA Swampworks)-Presentation
3D140	Nov 21 2019	The Proving Ground: Using Low Earth Orbit as a Test Bed for Manufacturing Technology Development-Presentation at 1st International Conference on 3D Printing and Transportation 2019
3D147	May 4 2019	Interview with CC24
3D150	May 1 2019	Interview with CC26
3D151	Nov 11 2020	Questions to “Blake” via email
3D154	Nov 9 2020	New NASA Partnerships to Mature Commercial Space Technologies, Capabilities-Press release
3D155	Nov 10 2020	Kennedy to Partner with Previous NASA Challenge Winner for Lunar Research-Press release
3D156	Jul 2020	3D-Printing Lunar and Martian Habitats and the Potential Applications for Additive Construction-International Conference on Environmental Systems 2020
3D157	Aug 28 2020	CHAPEA sole source contract description
3D159	Oct 1 2020	NASA looks to advance 3D Printing Construction Systems for the Moon and Mars-Press release
3D160	Sep 9 2020	Interview with “Blake”
3D161	Mar 18 2019	FAQ document for 3DPH Phase 3
3D162	Mar 29 2018	ISRU Construction & Excavation of Regolith-Presentation
3D163	Oct 2015	Additive Construction using Basalt Regolith Fines (Additive construction at Swampworks)-ASCE Earth and Space Conference 2015
3D164	May 2 2019	Interview with 3DPH participant 3D13SB1
3D165	May 2 2019	Interview with 3DPH participant 3D14SB1
3D166	Oct 1 2018	Technical Risk Reduction for the Mars Ice Home Habitat Concept-IAC 2018, IAC-18-F1.2.3

3D167	Apr 24 2019	Microgravity Effect on Microstructural Development of Tri-calcium Silicate (C3S) Paste-Journal article in Frontiers in Materials
3D168	May 6 2015	NASA Test Materials to Fly on Air Force Space Plane-Press release
3D169	Jan 23 2019	Concrete in Space Investigating cement solidification in a microgravity environment-Press release
3D171	2015	Completed technology project: Ice dome, Center Innovation Fund: LaRC CIF-Summary
3D172	Oct 7 2020	NASA Looks to Advance 3D Printing Construction Systems for Moon, Mars-Press release (Marshall Star)
3D174	Apr 23 2019	Designing Sustainable Homes on Mars and Earth-Press release (Penn State)
3D180	Sep 25 2017	Additive Construction with Mobile Emplacement (ACME)-IAC 2017, IAC-17-D3.2.1
3D181	Feb 14 2014	Fanuc arm arriving at Swamp Works for 3D printing of buildings-Twitter
3D185	Feb 24 2021	Interview with “Jude”
3D186	Oct 1 2020	NASA, BIG, SEArch+, and ICON team up to develop a lunar city-Press release
3D187	Aug 25 2017	Interview with CC5
3D188	May 9 2016	Interview with 3DPH participant 3D3HB1
3D189	Sep 2018	NASA’s Centennial Challenge for 3D-Printed Habitat: Phase II Outcomes and Phase III Competition Overview-AIAA Space 2018
3D190	Feb 20 2018	Current NASA Plans For Mars In Situ Resource Utilization-Presentation
3D191	Jul 31 2020	State of ISRU Construction at NASA-Presentation
3D192	Aug 24 2015	Space Environment & Planetary Civil Engineering Basics-Presentation
3D193	Apr 20 2021	Descriptions of benefits of the 3DPH Challenge via email
3D194	2015	How to 3D-print a habitat on Mars-Press release (Team Lavahive)
3D195	May 24 2016	Interview with 3DPH participant 3D6LB1
3D196	May 3 2016	Interview with 3DPH participant 3D1SB1
3D197	May 13 2016	Interview with 3DPH participant 3D5HB1
3D198	May 17 2016	Interview with 3DPH participant 3D4CS1
3D200	Nov 2019	LOD Specification Part 1 and Commentary (BIM Forum)
3D201	Sep 23 2019	Use of LOD in Mars Habitat Design Competition-Presentation
3D202	May 3 2019	Interview with 3DPH participant 3D15SB1
3D203	May 3 2019	Interview with 3DPH participant 3D17HB1
3D204	Apr 2017	Hypervelocity impact testing of materials for additive construction: Applications on Earth, the Moon, and Mars-14th Hypervelocity Impact Symposium 2017

3D205	Jan 21 2009	President's Memorandum on Transparency and Open Government - Interagency Collaboration-Memo
3D206	Sep 30 2015	Addressing Societal and Scientific Challenges through Citizen Science and Crowdsourcing-Memo
3D207	May 19 2017	Interview with 3DPH participant 3D7HB1
3D208	Aug 24 2017	Interview with 3DPH participant 3D10U1
3D209	Aug 25 2017	Interview with 3DPH participant 3D6L4
3D210	Aug 25 2017	Interview with 3DPH participant 3D12SB2
3D212	Nov 11 2020	CCP calculation of 3DPH Challenge ROI
3D213	Jun 30 2021	House Appropriation Committee ACOs for NASA
3D214	Sep 23 2021	Questions for "Jude" via email
3D215	Nov 3 2021	Overview of NASA's Moon-to-Mars Planetary Autonomous Construction Technology (MMPACT)-ASCEND Conference 2021
3D216	May 3 2019	Interview with 3DPH team 3D16
3D217	Sep 4 2018	Innovations in 3D Printing: Nathan Fuller, Form Forge-YouTube video
3D218	Aug 25 2017	Interview with 3DPH participant 3D11U2
3D219	2018	Martian 3Design Team (NWU) team roster
3D221	Feb 3 2021	Interview with CC30
3D223	Aug 5 2021	NASA CHAPEA mission description
3D224	Aug 6 2021	NASA is Recruiting for Yearlong Simulated Mars Mission-Press release
3D225	Aug 24 2021	Interview with "Billie"
3D226	Jan 18 2022	Quinn's written comments on an earlier version of this document
3D227	Feb 11 2022	Ash's written comments on an earlier version of this document
LE1	Feb 20 2020	Researcher notes at Lunar Excavation Challenge Workshop
LE3	Feb 20 2020	Lunar Excavation Challenge Workshop: all slides (briefing portions)
P3	Mar 1 2018	CCP Annual Report 2017
P5	Feb 22 2016	CCP Team presentation to Program Management Council
P13	Aug 17 2015	Outcome-driven open innovation at NASA-Journal article in Space Policy
P17	Feb 6 2014	The Road to Realizing In-space Manufacturing-Presentation
P18	Oct 24 2019	Interview with CC2
P19	Dec 7 2015	Researcher notes on CCP research kickoff meeting
P23	Nov 2010	DRAFT Human Exploration Destination Systems Roadmap, Technology Area 07

Table C.2: Formulation Team Minutes of Meeting referenced in the “Formulating the 3DPH Challenge” Case Narrative

Weekly minutes: “3D Habitat Centennial Challenge—Rules & Execution Team”
2017-02-02, 2017-03-02, 2017-05-04, 2017-05-18, 2017-06-15, 2017-06-22, 2017-07-13, 2017-07-14, 2017-07-20, 2017-07-27, 2017-08-03, 2017-08-31, 2017-10-26, 2017-12-20; 2018-01-04, 2018-01-11, 2018-02-08, 2018-02-15, 2018-03-22, 2018-03-29, 2018-04-11, 2018-05-31, 2018-07-12, 2018-07-17, 2018-07-19, 2018-08-02, 2018-11-15, 2018-12-13; 2019-01-31, 2019-03-21, 2019-03-28, 2019-04-03

Table C.3: CCP Minutes of Meeting referenced in the “Formulating the 3DPH Challenge” Case Narrative

Weekly minutes: “Centennial Challenges Program (CCP) Weekly Status”
CCP7, CCP10, CCP15, CCP20, CCP49, CCP71, CCP103, CCP124, CCP126, CCP132, CCP144, CCP147, CCP152, CCP154, CCP167

Appendix D—Data for "To Impose, To Incentivize, or To Subsume"

The below data table summarizes the 33 instances of problem formulation decisions made by the formulation teams in the CO_2-to-Glucose and 3DPH Challenges. It was created by coding the narratives in Appendix B and Appendix C, and served as the basis for the analysis in Chapter 5.

Table D.1: Problem Formulation Decision Instances

Contest and parameter	Solution knowledge	Details of solution knowledge	Solver knowledge	Details of solver knowledge	Action	Details of action
3DPH Phase 1: Habitat sizing	High	Seeker wanted realism in habitat design and knew its human factors' sizing requirements.	Low	n/a	Impose	Seeker determined the habitat size for a crew of four astronauts based on prior human factors work at the agency.
3DPH Phase 1: Life support system sizing	High	Seeker wanted realism in habitat design and knew its life-support components' sizing requirements.	Low	n/a	Impose	Seeker determined the footprint of the life-support equipment needed to be for a crew of four.
3DPH Phase 2: Feedstock material design	High	Seeker knew which (space) waste polymers to be used as feedstocks because of their abundance, vacuum, and radiation performance; knew local regoliths to be used for their abundance—both important for mass savings	Low	n/a	Incentivize[a]	A significant modifier to the solvers' score was based on the usage of specific waste and Martian materials as part of their feedstock: seeker didn't want to fully drive solvers' choices but wanted to encourage the use of some materials over others
3DPH Phase 2: Ratio of constituent materials in feedstock	High	Seeker wanted solutions with high fractions of ISRU materials (for mass savings) and performed tests to confirm a potential minimum	Low	n/a	Impose	Seeker imposed a minimum ratio on indigenous materials used in feedstock: pushes solvers to produce efficient yet viable materials

3DPH Phase 2: Material overhang slope	High	Seeker wanted printing systems that could create shapes with high overhang slope with no supporting material. They estimated that automated removal was possible	Low	n/a	Impose	Seeker imposed a specific structure to be printed by all solvers regardless of printing system: Pushes solvers to create a system with maximum usable volume
3DPH Phase 2: Printing method (to deposit feedstock)	High	Seeker did not want powder bed systems; they believed these were a significant hazard in microgravity (based on previous experiences).	Low	n/a	Impose	Seeker discouraged this printing method by disallowing particular (related) approaches
3DPH Phase 3V: 3D printed structure's pressure-retaining function of	High	Seeker did not want inflatable structures used to retain pressure; it would not push the development of sound structures. They were also afraid solvers would take the less costly/easy route	Low	n/a	Impose	Seeker imposed analysis on printed structural components, restricted other ways of accomplishing this function: pushes solvers to develop this printer (+feedstock) functionality
3DPH Phase 3V: Habitat sizing	High	Seeker wanted realism in habitat design and knew its human factors' sizing requirements.	Low	n/a	Impose	Seeker determined the habitat size for a crew of four astronauts based on prior human factors work at the agency.
3DPH Phase 3V: Life support system sizing	High	Seeker wanted realism in habitat design and knew its life-support components' sizing requirements.	Low	n/a	Impose	Seeker determined the footprint of the life-support equipment needed to be for a crew of four.

CO2-to-Glucose: Conversion method	High	Seeker wanted to push solvers towards more efficient (size, lag, maintenance/supply chain) systems; they did not want bio-based conversion systems. Seeker thought that, without this requirement, solvers would take the less costly/easy route	Low	n/a	Impose	Seeker excluded bio-based solutions of performing the conversion—pushed solvers to develop a physio-chemical conversion system
3DPH Phase 1: Feedstock material design	High	Seeker wanted ISRU materials as feedstock components to take advantage of mass savings. They had specific materials in mind	High	Seeker believed detailed materials development is expensive. Requiring this would burden them too much (and the seeker was working on rules for specific materials for subsequent phases)	Subsume	Seeker stated that feedstock should be ISRU materials, but nothing more. This allowed solvers to define what ISRU material they used. Here, the seeker assumed they would screen/assess the kinds of material that solvers envisioned for their concepts.
3DPH Phase 3V: Feedstock material design	High	Seeker knew which (space) waste polymers could be used as feedstocks because of their abundance, vacuum, and radiation performance. They also knew the most abundant local regoliths. Both of these would be important for mass savings	High	Material selection was no longer a priority, as the seeker thought the previous phase covered it extensively. So the seeker wanted to reduce the solvers' effort on materials (which was expensive) and redirect that elsewhere.	Subsume	Seeker stated that feedstock should be ISRU materials: Allowed solvers to define what ISRU material they used in their model. (Seeker assumed they would screen/assess the kinds of material that solvers envisioned for their concepts)

3DPH Phase 3C: Ratio of constituent materials in feedstock	High	Seeker wanted solutions with high fractions of ISRU materials (for mass savings) and performed tests to confirm a potential minimum	High	Seeker wanted to focus solvers' attention away from materials development (and to autonomy); some SMEs believed that this rule was too limiting for teams	Subsume	Seeker removed any ratio requirement but asked for materials "blends"; the seeker accepted the risk of much lower ISRU fractions
3DPH Phase 3C: Feedstock material design	High	Seeker knew which (space) waste polymers could be used as feedstocks because of their abundance, vacuum, and radiation performance. They also knew the most abundant local regoliths. Both of these would be important for mass savings	High	Seeker wanted to focus solvers' attention away from materials development (and to autonomy); the previous phase covered it extensively.	Subsume	Seeker kept the materials preference scale but reduced its points value drastically (it hardly affected their score). Though no longer a priority, the seeker would still be able to screen the solvers' material based on their knowledge
3DPH Phase 3C: Feedstock material safety	High	Seeker wanted materials that could behave as safe as needed for space applications, specifically their flammability and toxicity. They had previously used additives to reduce flammability	High	Seeker knew that flammability tests would be costly to perform and very specific to their industry. They also did not find suitable equivalents (i.e., no best fits).	Subsume	Seeker did not impose any safety requirements. They knew how to advance designs with respect to flammability and did not want to impose this burden on solvers
3DPH Phase 3C: Printer footprint	High	With space applications as the goal, the seeker knew the importance of minimal mass and volume for this equipment. But they acknowledged that the design could be "miniaturized" in later development stages	High	Seeker believed that these requirements would draw solvers' focus away from completing the other objectives	Subsume	Seeker did not include any footprint requirements related to spaceflight applications; they only described that the printer needed to be able to be transported on roads.

3DPH Phase 3C: Printed object's scale	High	Seeker wanted to force solvers to design printing systems that could print habitat-sized objects (they wanted full-sized prints). But they estimated that a less than full-scale object that might still push relevant development (even if it fell short)	High	Seeker believed the expenses of designing the equipment needed and printing a full-scale habitat would be too great	Best fit	Seeker scaled the habitat print down to 1/3rd scale: Believed that these solutions would still contain the dynamics they were interested in while being less expensive to create
CO2-to-Glucose: Production rate	High	Seeker wanted a system that could produce a glucose output that could support the bioreactors needed for a settlement, or at least a volume to be able to verify what the output is	High	Seeker was concerned that forcing solvers to produce these amounts would be too difficult, or worse, might discourage designs focused on lesser carbon compounds and not glucose	Best fit	Seeker did not impose production requirements besides saying they needed "enough" to be analyzed. They were concerned about the burden of requiring it or the adverse effects of imposing it. Instead, they asked solvers to design scalable systems.
3DPH Phase 2: Human interventions in autonomous operations	Medium	Seeker knew that autonomy was a key factor in making this system work. Remote interventions would be (more) justifiable in a mission scenario than manual ones, even if they preferred if both were zero	Low	Seeker believed that the capability to autonomously print the shapes they were prescribing was within the solvers' reach	Impose[a]	The rules imposed "semi-autonomous" behavior: physical interventions were not allowed during printing, though remote ones were.

3DPH Phase 2: Feedstock's water content	Medium	Seeker did not want water to be used as a construction material; it was needed for crew survival.	Low	n/a	Incentivize	Seeker added a significant (negative) modifier to the solvers' score based on water usage as part of the feedstock. Though they didn't want to completely exclude this possibility, they made sure to discourage it heavily
3DPH Phase 3V: Feasibility of construction processes	Medium	Seeker wanted algorithms that could efficiently convert the models that were created into a path for the print head and models that could simulate the construction of the 3D printed structure and supporting infrastructure	Low	n/a	Incentivize	Seeker incentivized higher fidelity models of the printer and its construction processes. They judged feasibility subjectively as no standards for efficiency of tool pathing algorithm, generally just wanted solvers to go in this direction
3DPH Phase 3C: Printed object's surface properties	Medium	Seeker wanted a printing system that could print flat and level objects, accurately printing the designs they wanted	Low	n/a	Incentivize	The seeker incentivized better surface properties on the printed objects
3DPH Phase 3C: Printed object's pressure retention	Medium	Seeker wanted hermetically sealed, robotically printed objects as these would improve the integrity of the habitats	Low	n/a	Incentivize	Seeker incentivized less leakage in printed objects (water or smoke)

3DPH Phase 2: Printed material's strength	Medium	Seeker wanted to characterize the solvers' materials (as they had no habitat design to comply with). Tests for compression, tension, slump tests would reveal their yield strength performance	Low	n/a	Incentivize	Seeker incentivized higher yield strength in printed objects
3DPH Phase 3C: Printed material's strength	Medium	Seeker wanted to characterize the solvers' materials (as they had no habitat design to comply with). Tests for compression, tension, slump tests would reveal their yield strength performance	Low	n/a	Incentivize	Seeker incentivized higher yield strength in printed objects
3DPH Phase 3C: Printed material's behavior under temperature stresses	Medium	Seeker wanted to characterize the solvers' materials (as they had no habitat design to comply with). Testing the number of thermal stress cycles would reveal their thermal performance	Low	n/a	Incentivize	Seeker incentivized a higher number of freeze-thaw cycles
3DPH Phase 3C: Printed material's impact resistance	Medium	Seeker wanted to characterize the solvers' materials (as they had no habitat design to comply with). Testing the printed objects' resistance to blunt object damage would reveal their impact/penetration resistance	Low	n/a	Incentivize	Seeker incentivized solutions that experienced less deformation at impact

CO2-to-Glucose: Output products	Medium	Seeker wanted to maximize the production of specific complex carbon chains (glucose especially): smaller can work, but longer ones are better sugars to feed the bioreactors on Mars:	Low	n/a	Incentivize	Seeker added a significant modifier to the solvers' score that was based on the production of longer carbon chains (glucose had maximum). While glucose is the most valuable (they could have written that alone), the other rungs are valuable too
3DPH Phase 3V: Habitat's architectural layout (space programming)	Medium	Seeker wanted functional habitat layouts; they knew about space programming and its efficiency. They referred to existing NASA habitation standards	Low	Seeker was looking to design / architecture community for their novel ideas for habitats: introduced the competition in order to not limit creativity	Incentivize	The seeker incentivized more novel / functional 3D Printed habitat layout ideas
3DPH Phase 3C: Autonomous operation	Medium	Seeker knew that autonomy was a key factor in making this system work. Remote interventions would be (more) justifiable in a mission scenario than manual ones, even if they preferred is both were zero	High	Seeker lowered their expectations of autonomy from solvers, the seeker believed that challenging full autonomy at this scale was too hard for solvers	Incentivize	Seeker deducted points from the solvers' score when solvers intervened in the print process (but physical more than remote ones)
CO2-to-Glucose: Conversion system footprint	Medium	Seeker wanted a conversion system that could fit in a NASA habitat design; they had a range that they targeted for these performance criteria (desktop sized)	High	Seeker thought that these requirements would push solvers towards these kinds of designs. However, they decided that this would be too much to impose on solvers / might restrict the somewhat successful solutions	Incentivize	Seeker incentivized lower values for the system's footprint, power, and ease of operation (as a bonus round).

CO2-to-Glucose: Sample purity	Medium	Seeker wanted to reduce/eliminate potential contaminants in the sample that would impede bioreactor usage. They believed that the sample could be purified through extra steps (outside of the contest)	High	Seeker believed that including this function in the competition would make it too hard/costly to solve	Subsume[a]	Seeker did not impose any purity requirements (or incentives) besides mentioning that they wanted to minimize it.
3DPH Phase 1: Novelty in architectural design	Low	Seeker team had little architectural design experience; some didn't care about it; referred solvers to existing NASA habitation standards	Low	Seeker was looking to design / architecture community for their novel ideas for habitats	Incentivize	Seeker incentivized more novel and innovative 3D Printed habitat designs

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[a] Outliers to the patterns in our data; these are explained in Chapter 5.

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Author(s): Ademir Vrolijk, Monsi C. Roman, Zoe Szajnfarber

To be published in the journal (the "Journal"): Research-Technology Management (ISSN: 0895-6308)

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Roman, Monserrate C. (MSFC-ST21) <***@nasa.gov> To: Ademir Vrolijk <***@email.gwu.edu>

Wed, Apr 6, 2022 at 6:30 PM

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You have my permission and excitement as you get closer to finish.
Let me know if you need anything else, pls.

Regards
Monsi

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>
> Best regards,
>
> Ademir
>
> --
> **Ademir Vrolijk, Ph.D.**
> Department of Engineering Management and Systems Engineering
> The George Washington University
> avrolijk@gwu.edu | Twitter | LinkedIn

Vrolijk, Ademir-Paolo <*@email.gwu.edu>**

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Zoe Szajnfarber <***@gwu.edu> Reply-To: ***@gwu.edu
To: Ademir Vrolijk <***@email.gwu.edu>

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